



# Contingency Power Study for Short Haul Civil Tiltrotor

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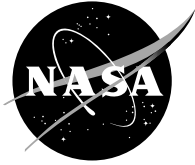
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# Contingency Power Study for Short Haul Civil Tiltrotor

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National Aeronautics and  
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Glenn Research Center

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## 1.0 SUMMARY

AlliedSignal Engines (AE) defined a number of concepts that significantly increase the horsepower of a turboshaft engine to accommodate the loss of an engine and enable the safe landing of a twin engined, 40-passenger tiltrotor. Operation at this contingency rated power was required for only 2.5 minutes. These concepts were ranked on the basis of power augmentation capability, direct operating costs (DOC), and safety. The following were selected for further analysis:

- Water/Methanol Injection
- Better Power Turbine Than Required
- Secondary Combustor For Interturbine Reheat

The power augmentation ratio, percent change in DOC, and DMC of these concepts relative to the AE Baseline engine are shown in Table 1. Note that engine DMC does not parallel vehicle DOC. Vehicle DOC, a NASA empirical calculation which is a function of engine horsepower, does not necessarily reflect DMC influences due to different engine configurations. However, VASCOMP DOC results were not adjusted for AE results for NASA comparison consistency.

**Table 1. Summary of Contingency Concepts.**

CONCEPT		CRP/TOP*	Δ DOC**	Δ DMC**
Water / Methanol Injection	2000 pph	1.26	-2.4%	-5.7%
	4000 pph	1.31	-3.0%	-6.9%
	5000 pph	1.32	-3.3%	-7.2%
Better Power Turbine Than Required		1.41	-4.2%	-2.1%
Secondary Combustor For Inter-Turbine Reheat		1.70	-5.7%	+6.4%
*Contingency Rated Power (CRP) to TakeOff Power (TOP)				
**Results Relative To AE Baseline Engine. Negative Sign Indicates Reduction In Cost				

A primary consideration was the increased engine operating temperatures needed to produce an augmented power level. The selection of the AS812 engine facilitated these concepts since its power turbine could be upgraded to a higher technology level. Consequently, these concepts would not be applicable to an engine which already used high temperature turbine material and advanced cooling schemes.

## 2.0 INTRODUCTION

NASA is encouraging the U.S. aerospace industry to develop a Short Haul Civil Tiltrotor (SHCT) commuter aircraft as shown in Figure 1 and Figure 2. Toward this end, NASA is supporting and coordinating research into the technologies necessary to meet this goal. A prime consideration in a tiltrotor operation is the loss of an engine. The propulsion system must have the intrinsic capability to accommodate the loss of an engine and step up to provide the required power to either continue the mission or land safely. In addition, the propulsion system must offer low operating costs to make the tilt rotor economically viable. The successful tiltrotor will initially fill a market niche that combines the vertical takeoff capabilities of helicopters with the high-speed cruise offered by fixed-wing turboprop airplanes.

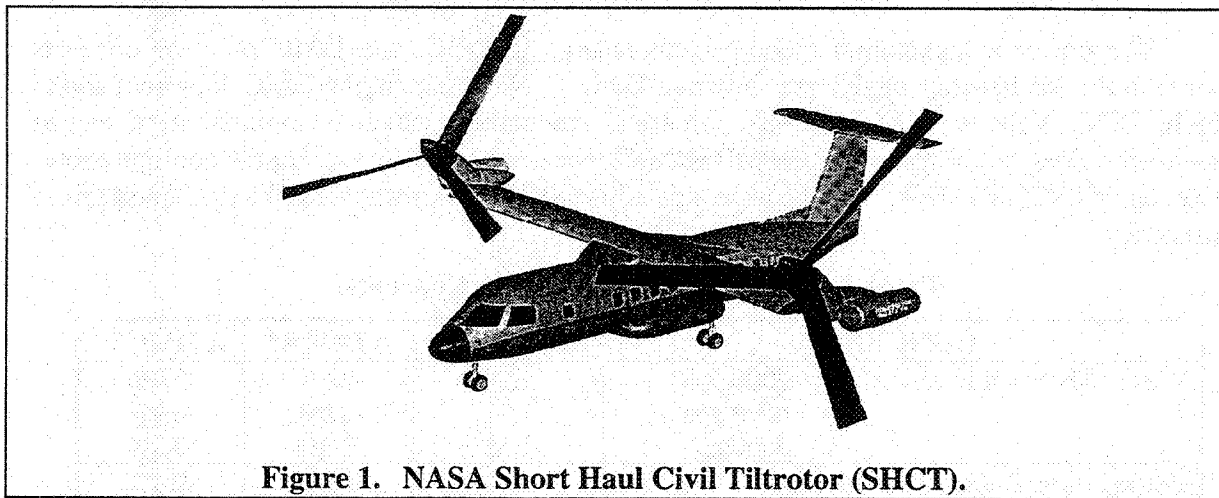
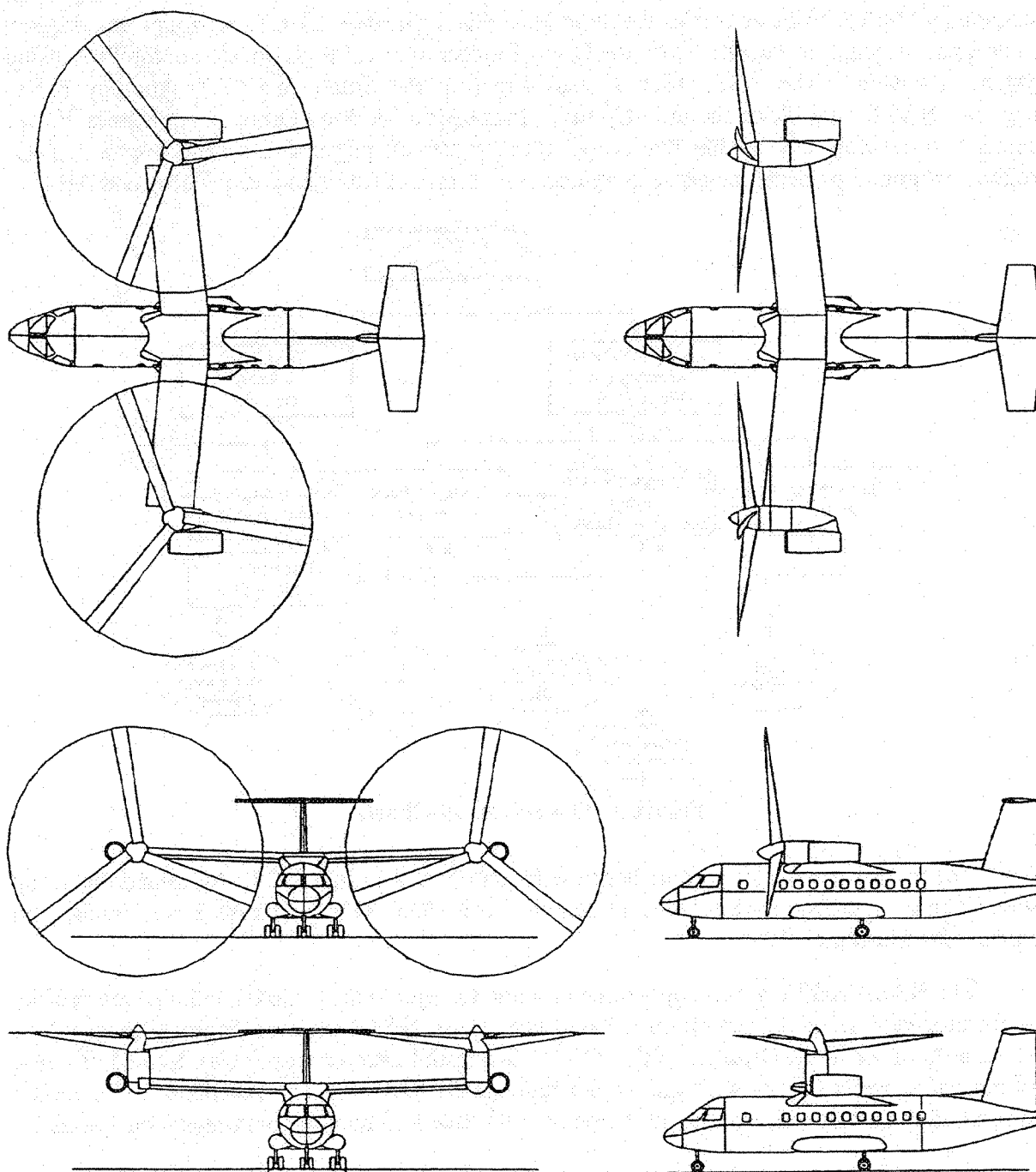


Figure 1. NASA Short Haul Civil Tiltrotor (SHCT).

Current design practice sizes each tiltrotor engine such that it can provide the maximum total vehicle power required when operated at the maximum turbine inlet temperature. This results in a heavier and more inefficient propulsion system than required for normal operation. Consequently, the tiltrotor design is compromised; heavier, costlier (both acquisition and operating), and too powerful. The ideal tiltrotor engine, in a twin-engine installation, would be sized to provide half the maximum required horsepower and would never fail. While the ideal tiltrotor is not possible, its concept can be used as the yardstick to measure candidate propulsion systems against. The goal of this study is to develop a propulsion system with contingency power capability that approaches the economics of an ideal system.

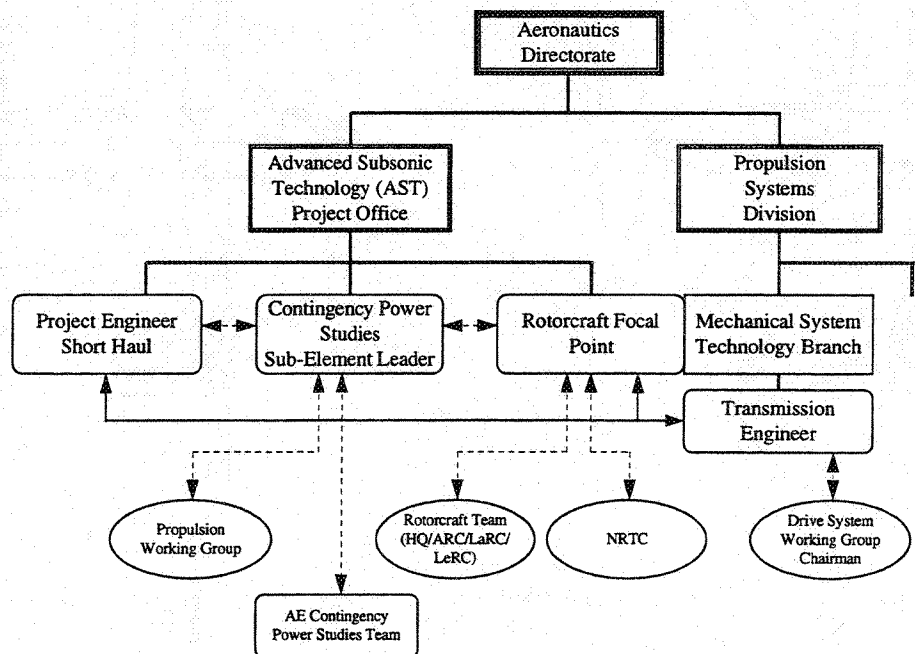
AE submits the results of the following study in response to NASA Small Engine Technology Proposal 4510.251.2, "Contingency Power Study For Short Haul Civil Tiltrotor". AE examined methods to attain power levels significantly higher than takeoff power, for short duration, to accommodate the loss of an engine. These increased power levels were ranked on the basis of economy and safety. This contingency rated power (CRP) level is defined per FAA criteria for a 2.5-minute One Engine Inoperative (OEI) contingency rating. CRP is to be used only in the event that one of the vehicle engines becomes inoperative. The available time at this power is 2.5 minutes by design without incurring any engine damage. Further, and again by design, CRP can be used three times over the life of the engine without sustaining damage or incurring additional costs above that of normal system use.



**Figure 2. NASA Short Haul Civil Tiltrotor 3-Views.**

### 3.0 BACKGROUND

NASA has initiated contingency power studies through the Advanced Subsonic Technology (AST) Office as part of the Short Haul Civil Tiltrotor (SHCT) program. In addition, the program is being coordinated with the Lewis Rotorcraft Focal Point located in the Propulsion Systems Division. The AST office is also directing the Small Engine Technology (SET) program. NASA established the industry-based Propulsion Working Group, Contingency Power Element, to develop and demonstrate a civil tiltrotor aircraft propulsion system over a 3 phase program. Figure 3 presents the general organizational infrastructure between NASA and AE.



**Figure 3. Organization Chart.**

The propulsion working group began work on Phase 1 in July 1994. AE joined the group under Contract Number NAS3-27481 in March 1995. The RFP for Phase 2 was issued and Phase 1 ended in March 1996.

The NASA SHCT group defined the baseline tiltrotor vehicle model and mission profile. The tiltrotor vehicle model definition is based heavily on NASA tiltrotor empirical data; which include tests of the V-22 Osprey and the XV-15. An initial tiltrotor model was defined on 7/94. Preliminary analysis results with this model highlighted necessary modifications to the model and resulted in an updated baseline definition on 4/95 (See Reference 1 for comparison details).

The 4/95 baseline and mission profiles were made available to the Contingency Power Studies group in terms of VASCOMP II program input. VASCOMP is the acronym for V/STOL Aircraft Sizing and performance COMputer Program. This program was developed by the Boeing VERTOL Company in 1968. It underwent three major Boeing revisions, the last in 1980. NASA has under taken the responsibility to update a general industry version since.

The NASA Contingency Power Studies group distributed the tiltrotor model and mission profile definitions to the participating industry representatives on the propulsion working group committee. These representatives included AE, Allison, and General Electric (GE). NASA supplied electronic files containing the most current FORTRAN source code for VASCOMP and an input file necessary to model a 4/95 baseline tiltrotor. This input file also implicitly defined the mission profile and miscellaneous engine and aircraft sizing parameters. Reference 1 documents these details. A hard copy of the glossary, Volume 1, and Volume 2 of the VASCOMP instruction manual were also provided.

The NASA baseline engine in the tiltrotor model was based on a generic, nonproprietary turboshaft whose origins lay with a GE engine, Model GLC38. VASCOMP scaled these operating characteristics to meet the vehicle requirements. This engine has a 2.5-minute CRP available by a "throttle push" during OEI operation. This provides a power level nominally 3.5 percent higher than normal takeoff rated power.

Based on NASA payload and mission requirements and using the NASA tiltrotor vehicle model, AE performed this study to identify and analyze OEI contingency power propulsion system concepts. Whether engine or airframe based, these propulsion systems would provide significantly increased power levels for OEI operation, completely safe operation, a cost advantage over current approaches, and be based on advanced technology levels equivalent to Entry-Into-Service (EIS) 2005. AE fulfilled the statement of work (SOW) by completing the following four tasks:

**Task 1** - Define a baseline engine model sized for the tiltrotor power requirements. Use technology levels consistent with Entry Into Service (EIS) in the year 2005. Quantify baseline tiltrotor operating characteristics by using the engine model in the NASA vehicle model/mission definitions. Define Direct Operating Costs (DOC) and key engine related costs (including but not limited to engine acquisition, maintenance, and operational).

**Task 2** - Identify and detail various contingency power propulsion system concepts that have the potential for significant power provision. Choose the top candidate contingency power systems based on safe operation, total power, and minimum DOC.

**Task 3** - Define propulsion systems details for each of the viable concepts. Describe system size, weight, and cost savings relative to the baseline engine (including but not limited to design point, engine life, engine maintenance, and DOC).

**Task 4** - Identify preliminary design scope by defining the sections/components of the baseline engine that will require design and development to enable implementation of the contingency power concepts. Schedule, cost, and probability of success are addressed.

## 4.0 TASK 1: AE BASELINE ENGINE DEFINITION

A baseline engine model is established in this section to enable various OEI technology concepts to be defined and analyzed. The performance characteristics, weight, mission performance, acquisition cost, DMC, and DOC of this engine were determined and used as the common reference point to judge the OEI concepts.

### 4.1 AE Baseline Tiltrotor Engine

The baseline engine is derived from a AE turboshaft engine in the size class required by the tiltrotor. This engine was analytically infused with advanced technologies equivalent to that for EIS 2005. These technologies were defined as the result of NASA SET studies and resulted in significant power improvements. As a result, this advanced engine had to be scaled down to meet the needs of the tiltrotor at the sizing point.

#### 4.1.1 AS812 Engine

The tiltrotor mission profile provided by NASA indicated an engine rated at sea level, static, ISA day conditions in the 10,000 HP class was required. AE selected the AS812 turboprop engine (see Figure 4). This engine is a two spool turboprop engine. It is based on the AS807 engine proposed for the DeHavilland Dash 8-400 Regional Turboprop airplane. The AS812 has 180 degrees Fahrenheit of deterioration margin to enable regional service.

The AS807 core compression system consists of a seven-stage axial compressor followed by a single-stage centrifugal compressor. It is designed with a mass flow pumping capacity of 36 lb/sec. Horsepower to drive the compression system is provided by a two-stage, high-pressure turbine. The AS812 uses this “common core” and adds a low-pressure spool comprised of a three-stage booster compressor and a three-stage power turbine. The constant-speed free power turbine drives the booster compressor and supplies the output power. This power would normally be input to the supplied gearbox designed to step down the 11,000 rpm shaft speed and drive a propeller. The AE supplied gearbox was eliminated since tiltrotor installation supplies its own.

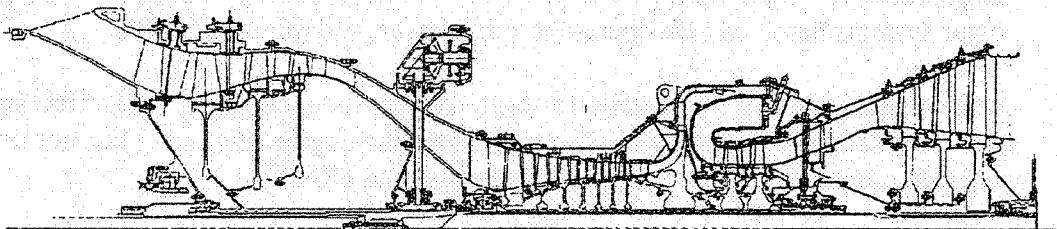


Figure 4. AS812 Engine.

The AS812 has an Automatic Power Reserve (APR) level nominally 15 percent greater than its 5-minute TakeOff Power (TOP) rating. This power is obtained through a throttle push to higher operating temperatures and it is limited to 170F above TOP. This rating is intended only

for emergency use and consequently is only available in the event of an engine failure. Operation at this temperature was limited to 2.5 minutes per a Contingency Rated Power (CRP) definition.

#### **4.1.2 Advanced Technology Modifications**

NASA Small Engine Technology (SET) performance improvements consistent with year 2005 Entry-Into-Service (EIS) were incorporated into the engine design. The general goals of the SET program are presented in Table 2.

**Table 2. NASA SET Performance Improvements (2005 EIS).**

<b>CATEGORIES</b>	<b>SET GOAL</b>
DOC	10-15%
Emissions (Noise & Comb.)	Compliance
Mission Fuel Burn	10%
Engine Weight	10%
Reliability & Maintainability	10%
Engine Cost	No Change

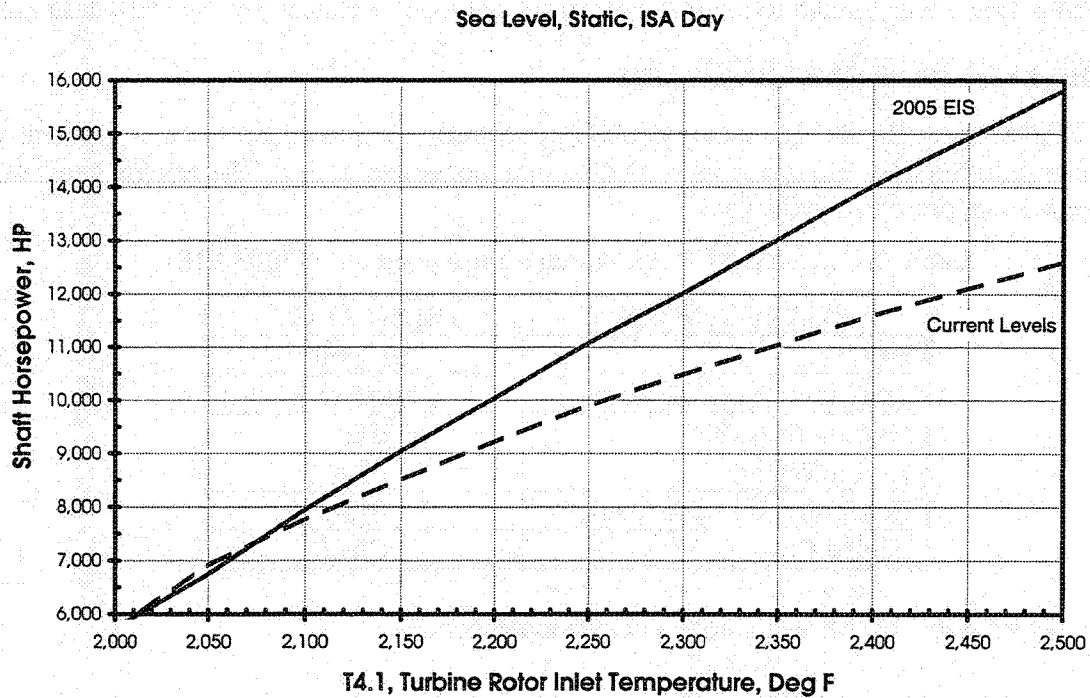
These goals were met by AE technological developments in:

- Advanced Film Cooling
- Turbine Disk Cavity Cooling
- Affordability-Driven Cooled Turbine
- Centrifugal Titanium Compressor
- Finger Seals

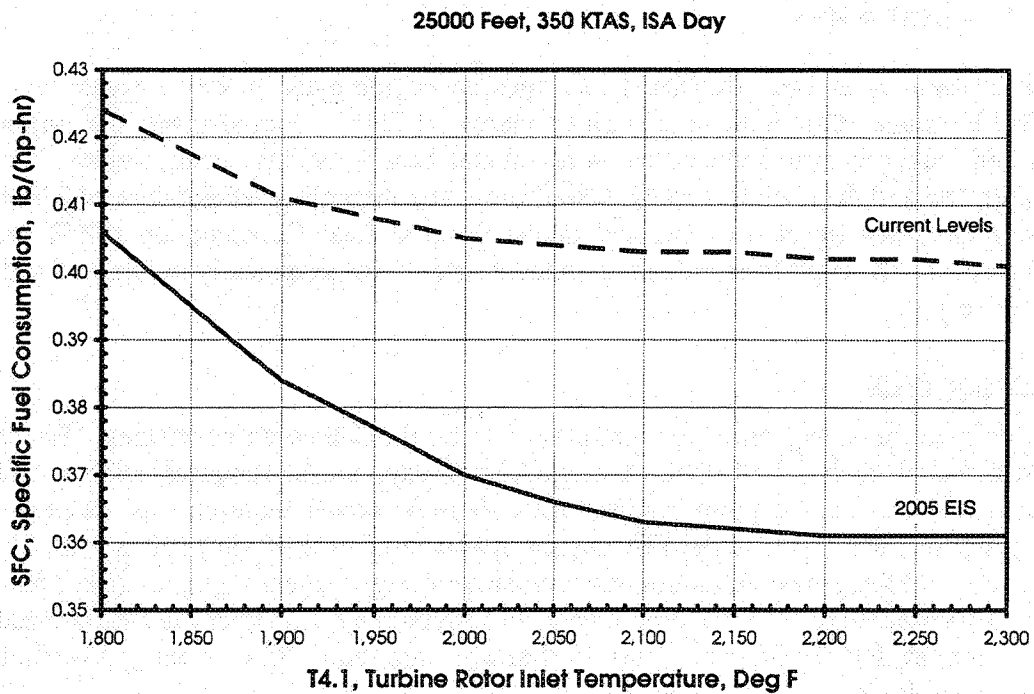
Studies in these areas were translated into specific engine cycle model impacts. As a result, the AS812 turbine rotor inlet temperatures increased 200F. Furthermore, the turbine cooling flows and leakages were reduced as an additional benefit of these technologies. The cycle was reoptimized and matched to a rated takeoff now at a maximum temperature of 2700F. Available power increased by 50 percent, and cruise Specific Fuel Consumption (SFC) was reduced by 10 percent. These performance improvements are shown graphically in Figure 5 and Figure 6, respectively.

#### **4.1.3 Engine Sizing Point**

NASA defined the sizing point for the tiltrotor to be the following conditions: Hover-Out-of-Ground-Effect (HOGE), 2000 feet, static, ISA+20C day, and contingency rated power. AE analysis confirmed this sizing point imposed the maximum power requirements, exceeding those necessary at either sea level, static, ISA day, normal takeoff or 25K feet, 350 KTAS, ISA day, cruise power. NASA power requirements predicted during convert segments (transitions from hovering to forward flight or vice versa) were for reference only. Other typical rotorcraft sizing criteria such as HIGE OEI and 150 feet/minute minimum ROC during 30-minute operation were not applicable.



**Figure 5. AS812 Baseline Power With and Without SET Improvements.**



**Figure 6. AS812 Cruise SFC With and Without SET Improvements.**

#### 4.1.4 Baseline Engine Sizing

The advanced technology engine derived from the AS812 was resized such that at the contingency rated power (CRP) temperature it met tiltrotor OEI power requirements at the sizing point. This engine is the AE Baseline tiltrotor engine. This engine sets the benchmark performance levels against which the contingency power concept engines are compared. Table 3 compares the primary performance parameters of the current AS812 engine, the AS812 engine with SET, and the AE Baseline tiltrotor engine.

**Table 3. AE Baseline Engine Development Progression.**

Parameter	Units	AS812 (Current Levels)	AS812 with SET (EIS 2005)	AE Baseline Tiltrotor Engine
<b>Sea Level, Static, ISA Day</b>				
SHP	HP	10,488	15,804	9,093
SFC	Lb/(HP-Hr)	0.433	0.363	0.366
T4.1	Deg F	2,300	2,500	2,500
$W a \sqrt{\theta_2 / \delta_2}$	PPS	81.7	78.1	47.2
OCR	---	39.2	36.5	36.6
<b>25000 Feet, 350 KTAS, ISA Day</b>				
SHP	HP	4220	6458	3522
SFC	Lb/(HP-Hr)	0.402	0.361	0.361
T4.1	Deg F	2100	2300	2300
$W a \sqrt{\theta_2 / \delta_2}$	PPS	78.1	62.4	37.6
OCR	---	36.5	29.6	29.3
SHP = brake Shaft HorsePower SFC = Specific Fuel Consumption T4.1 = High Pressure Turbine Inlet Temperature $W a \sqrt{\theta_2 / \delta_2}$ = Corrected Engine Inlet Airflow		OCR = Overall Compression Ratio ISA = International Standard Atmosphere KTAS = Knots True Airspeed EIS = Entry Into Service		

The sizing process was iterative. Initially, the sizing point horsepower requirements of the tiltrotor with the NASA engine was used. This was refined as the engine weight and Specific Fuel Consumption (SFC) over the mission were matched to the tiltrotor. Specific calculation details used to size the engine are shown in Appendix I.

The AE Baseline engine has a 38 lb/sec flow capacity. On a sea-level, static, ISA day, at the contingency temperature of 3130 Rankine (R), the engine produces 10,716 HP. The nominal power rating of this engine, at the normal takeoff temperature 2960R, is 9,093 HP.

AE exercised the option defined by Task Order 48, Task 1 Amendment (e), and developed the AE Baseline engine model rather than use the one provided by NASA. Comparisons between the AE and NASA Baseline engines define the differences between these engines.

## 4.2 Engine Weight

Horsepower rating and engine core flow capacities enabled engineering drawings to be completed and components scaled relative to the AS812. Based on this parts workup, the horsepower produced, and the weight of the AS812, the scaled engine dry weight was estimated at 1,080 lb. The engine weight was a required input for the mission analysis.

## 4.3 Mission Analysis

VASCOMP scaled the aircraft characteristics as a result of the input engine capabilities and weight. Then using the mission profile, the mission performance of the AE Baseline engine was established.

### 4.3.1 Aircraft Characteristics

The tiltrotor was defined per the NASA SHCT in April 1995. The primary features are identified in Table 4. As shown in Figure 1, the aircraft is a twin-engined, high-wing, T-tailed vehicle. The engines are fixed and do not tilt with the rotor. Program VASCOMP initially operates as a design synthesis code to size the vehicle based on key input design parameters, defining the geometry of individual components making up the tiltrotor. The weights of these components are empirically estimated. The power requirements are identified, the engine scaled (AE disabled this option and input a fixed engine), and the transmission sized accordingly. A drag build-up is completed and a polar defined for mission analysis purposes. The fuel required to achieve the design mission profile is calculated and becomes part of the design gross weight. This process is iterated until the resulting vehicle matches the design inputs and constraints.

**Table 4. Short Haul Civil Tiltrotor Design Criteria.**

ASPECT	DESCRIPTION
Aircraft	40-Passenger Commuter Tiltrotor
Crew	Two Pilots and One Attendant
Design Range	600 NM, Emphasis on 200 NM Legs
Payload	8000 lb 40 PAX at 200 lb Each, Four-Abreast
OEI Design Point	OEI HOGE at CRP; 2,000 Feet; ISA+20C; Static; TOGW
Cruise Design Point	25,000 Feet; ISA; 350 KTAS
Reserves	Fuel For 45 Minutes Cruise At LRC; 25K
Engines	Two Turboshaft Engines With Contingency Power Ability

### 4.3.2 Engine Characteristics

Program VASCOMP requires engine operating characteristics (horsepower, fuel flow, gas generator speed, and power turbine speed) to be input as a functions of turbine operating temperatures and flight mach numbers. Table II-1 contains the tabular input definition of the AE Baseline engine. VASCOMP engine operating limits were not used. Instead, the limits and schedules inherent in the AE cycle model were relied upon. The VASCOMP calculated weight, a function of the maximum sea level static power, was adjusted with a delta weight adder to reflect the 1,080 pounds actual weight.

Nacelle geometry and corresponding drag characteristics were calculated by VASCOMP. The smaller geometry of the AE Baseline engine would have resulted in a slightly lower nacelle drag (reference Table 5). In cruise, it would have decreased about 143 pounds, 3.0% of the total vehicle drag. Efforts were not made to adjust the drag due this magnitude and the preliminary design nature of the program.

**Table 5. Nacelle Characteristics.**

	Length Feet	Diameter Feet	Wetted Area Square Feet	Cruise Drag Pounds
VASCOMP Nacelle	10.5	5.8	382	349
AE Engine Nacelle	9.4	4.5	220	206
NOTES: (1) Cruise Defined As 25K / 350 KTAS / ISA Day (2) Area And Drag Results Based On 2 Nacelles (3) Drag Areas Calculated Assuming Fully Turbulent Boundary Layer, $C_F = .455 / (\log Re)^{2.58d}$ (4) AE Engine Nacelle Assumes: Six Inches Between Inner and Outer Nacelle Skins, Nozzle Length Equal To Exit Flange Radius, And A No Inlet Diffuser Forward Of The Front Flange.				

#### 4.3.2.1 Input Development

The flight Mach number range was adequate as defined by NASA: Mach 0.0, 0.2, 0.4, 0.5, 0.6, and 0.7. However, VASCOMP tends to have verbose warning messages when engine tables are extrapolated. Consequently, subground idle and super-CRP temperatures were defined to prevent these from occurring. Modification of the source code enabled 10 x 10 matrices to be input as opposed to the original 6 x 8 size. These dummy temperature ratings do not reflect actual engine operating characteristics. In addition, the expanded matrix allows further definition of engine characteristics over the normal region of operation. General guidelines used select temperature ratings and include:

- (1) Subground idle point. A fictitious point (i.e., idle ratios divided by 10) input to prevent VASCOMP extrapolation error messages.
- (2) Ground idle engine rating.
- (3) Flight idle engine rating
- (4) Part Power
- (5) T/O power level required by the aircraft (NOT engine takeoff power rating).
- (6) T/O Engine Rating
- (7) CRP engine rating (Power Fraction = 1.0 )
- (8) Super-CRP. Similar to (1) in that it is made up to prevent error messages.

The base option in program VASCOMP calculates weight of the primary engines (Wep) based on the following equation:

$$Wep = SK3 \cdot \frac{DAM7}{2} + SK4 \quad \text{or}$$

$$Wep = 0.09688 \cdot \frac{21,432}{2} + 169.9 = 1,208lb$$

This weight exceeds the 1,080 pounds of the AE Baseline. Consequently, a propulsion system delta weight adder of -256 pounds (twice the difference of 1,208 and 1,080 for the twin engine installation) was input to correct the VASCOMP propulsion system weight.

### 4.3.3 Mission Profile

The mission profile is illustrated in Figure 7. This profile was defined in the 4/95 baseline tiltrotor input file and is consistent with Reference 1. Program VASCOMP analytically “flies” major mission segments, not a continuous mission.

VASCOMP scaled the tiltrotor to meet this mission profile based on the input AE Baseline engine operating characteristics and the engine weight. The AE Baseline engine was mission optimized, trading off any excess power in exchange for lower engine weight and SFC.

### 4.3 Mission Fuel Burn

The mission fuel burns with the AE Baseline engine were 1661 and 4280 lb of fuel for 200 and 600 NM ranges respectively. The AE Baseline engine requires 5 to 7 percent more fuel on board than the NASA Baseline engine.

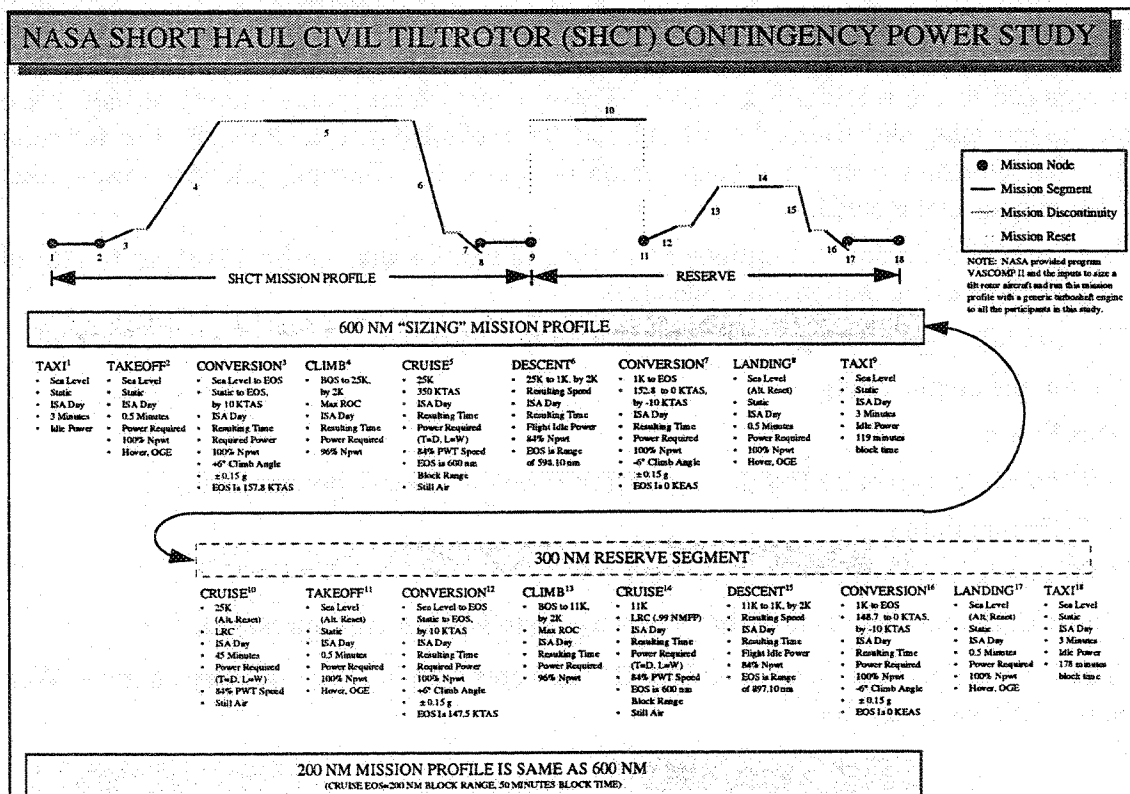


Figure 7. Tiltrotor Mission Profile.

#### 4.4 Engine Acquisition Cost

AE has estimated the acquisition cost of the AE Baseline engine at \$1,952,000. These costs are based on 1995 dollars and are for a mature engine using year-2005 technology levels. The VASCOMP prediction was significantly different at \$1,216,322. However, Figure 8 indicates the acquisition cost is in the market range for engines of this size class.

#### 4.5 Engine Direct Maintenance Cost

AE calculated the AE Baseline engine DMC for both the 200 and 600 NM mission profiles as if the tiltrotor were flown on either exclusively. Consequently, the actual 10-year cumulative average cost would be within the range of \$39.81 to \$51.58 per hour of operation. A detailed break down of AE Baseline engine DMC costs is presented in Appendix III, Tables III-1 and 2. AE calculated DMC is significantly lower than the VASCOMP engine maintenance costs results of \$120.33 to \$159.88 per hour. All results are based on 1995 dollars.

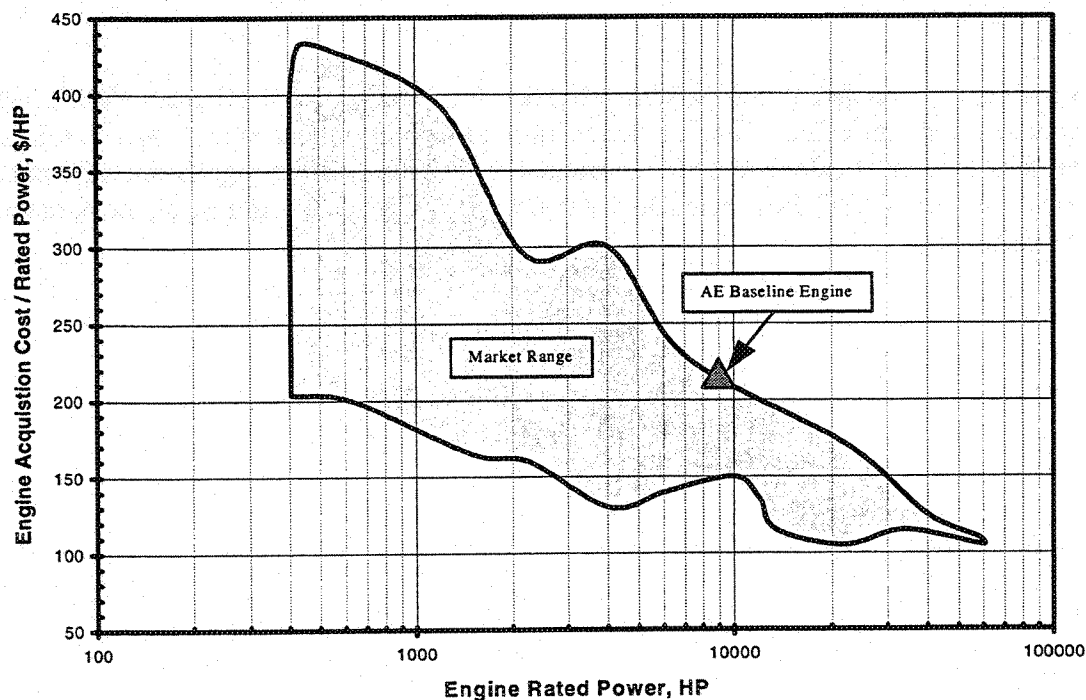


Figure 8. AE Baseline. Engine Acquisition Cost Versus Market Range.

##### 4.5.1 AE DMC Calculation Methodology

The AE Direct Maintenance Cost (DMC) Model is a component level process simulation model. Each engine type has its own unique data base that can be loaded for execution by the model. A data base contains a baseline set of global input parameters and a series of

maintenance parameters on a piece part level for the maintenance cost drivers in the engine. The contents within the data base make each part uniquely sensitive to age related maintenance action rates over time, reparability, cost per maintenance action, location of the maintenance action, component price, its sensitivity to gaspath temperatures, and steady state and cyclical stresses. Global inputs set the operational and logistical profile for the mission being modeled. Flight time, annual utilization, two or three level maintenance, maintenance capability at each level, labor rates and efficiencies, reliability growth, delivery schedule and engine power settings are some of the constraints being modeled. During execution, the number of maintenance events for each part is estimated for up to 15 years. The maintenance events are then multiplied by both the man-hour cost and the average material cost per event. This continues on a part level until the costs for the entire engine are accumulated.

#### **4.6 Tiltrotor Direct Operating Costs**

The AE Baseline engine resulted in a tiltrotor with a total trip DOC of \$2,121.37 for a 200-nm range, or \$4,555.99 with a 600-nm mission range as calculated by program VASCOMP. This translates to \$6.60 to \$9.22 per mile. With 40 revenue-paying passengers, these costs are \$0.1650 to \$0.2304 per seat mile. This DOC is almost 2% higher than the NASA Baseline engine.

To maintain a consistent comparison reference for NASA, the DOC from VASCOMP was not adjusted for AE calculations of acquisition or Direct Maintenance costs. AE has provided these independent calculations for additional information. Since significant differences exist between AE and VASCOMP calculated engine costs, the actual aircraft direct operating costs will be different.

## 5.0 TASK 2: CONTINGENCY POWER CONCEPT IDENTIFICATION

AE formed a Contingency Power Study Team to define potential technology concepts that would deliver additional power during OEI operation. This team was created by expanding on the basic tiltrotor team with representatives from the major technical disciplines as shown in Figure 9. Candidate concepts were brainstormed. From these potential concepts, the most promising were chosen for more detailed analysis.

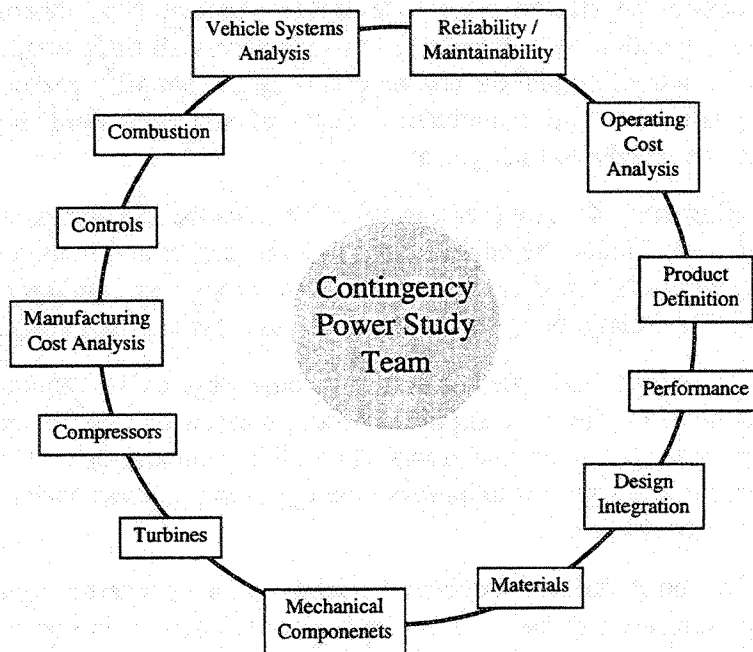


Figure 9. AlliedSignal Contingency Power Study Team.

### 5.1 Proposed Contingency Power Concepts

This team brainstormed over 20 potential contingency concepts. The initial question posed was “How might a turbine engine provide significantly more power for 3 minutes in an emergency situation?”. Then the civil tiltrotor application was described and a follow-up question was “How else might a tiltrotor land safely after losing one engine?”. The ideas, in no particular order, included:

- (1) **Pressurized Air Turbine (PAT) System:** A turbine linked to the rotor drive train can be powered by a stored source of compressed air or gas. This turbine can be an auxiliary mounted aircraft component, or an engine component. If the power turbine of the inoperative engine is still useable, power could be regained without effecting the normal operation of the remaining engine. Otherwise the PAT system would increase the power output of the operating engine above nominal levels.
- (2) **APU In Drive Train:** An APU (perhaps one significantly oversized), normally providing accessory power only, is included in the drive train. It is accelerated to full power in the event of the loss of a main engine to partially make-up for the main engine loss. The

operating engine would be accelerated to contingency power levels to provide the remaining power needs. The advantage of operating the main engines more efficiently would have to overcome the additional weight, drag, and inefficient operation of the APU.

- (3) **More, Smaller Engines - 3:** The tiltrotor has three engines contained in or on the fuselage all driving the same gearbox. The engines are sized such that any two provide efficient cruise performance and have contingency capability that would enable a safe landing. The third would normally be started prior to a hover segment (i.e., takeoffs or landings). Scheduled engine operation would spread life usage across all three engines equally. This also has the potential to eliminate the engine pod drag and simplify gearbox cross-shafting. Obviously the acquisition and maintenance costs of adding a third engine have to be overcome by the advantages of this system.
- (4) **More, Smaller Engines - 4:** Another variation includes the tiltrotor having four engines, two driving each rotor. Thus, the engines could all be smaller and in the case of losing any one, the other(s) would be sized to pick up the load through its contingency power rating. This system could potentially be designed to eliminate cross-shafting altogether.
- (5) **"Turbocharger":** Another compressor and/or turbine stage exists "somewhere". It could either be another stage on the main engines or located elsewhere on the aircraft. Normally it is not used. Upon loss of an engine, doors or variable geometry open, connecting it to the operating engine, turbocharging it to increase the operating pressure ratio, flow, and speed; thus producing additional power.
- (6) **Rocket Fuel Powered Auxiliary Turbine Linked To Drive Train:** Again, an additional turbine would be aircraft mounted. It is either clutched or slip linked to the drive train. Solid propellant rocket fuel would be burned and expanded through the auxiliary turbine and the power generated input into the gearbox. This enables the main engines to be normally sized. The ability to control the auxiliary turbine and the amount of solid fuel propellant need to be quantified. The use of solid propellant fuel would complicate system functionality checks prior to takeoff.
- (7) **APU Linked to Core Via AGB:** An APU, normally nonoperating, is linked to the core engine through its accessory gearbox. The APU would be started prior to a hover segment. In the event of an engine failure, the APU would be automatically accelerated and its power contributed to the operating engine's contingency output.
- (8) **Reheat Before Power Turbine:** A secondary combustor exists in the interturbine duct between the High Pressure (HPT) and Power (PWT) turbines. Normally this combustor is unlit and the engine suffers the pressure loss. During OEI this combustor is ignited and additional power is generated to achieve contingency power levels.
- (9) **External Secondary Combustor System:** A secondary combustor exists "somewhere" on the tiltrotor. This would be a "sore thumb" type combustor either mounted on each engine and connected with variable geometry, or a single airframe mounted combustor ducted to both engines. Normally it is unlit and is not a part of normal engine operation. With an OEI event, flow is diverted through the combustor, ignited, and additional power generated.

- (10) **Impingement Nozzles In The Power Turbine:** Upon losing an engine, an external source of pressurized air or gas is directed onto the power turbine blades themselves to provide additional power. This source could be from a PAT system (see concept 1) or from solid propellant rocket fuel combustion. Again this would ideally be performed on the inoperative engine itself to regain power.
- (11) **Fuel Used for Turbine Cooling:** During an OEI incident, fuel is added to the turbine cooling air of the operating engine, increasing turbine cooling efficiency, enabling higher operating temperatures through a throttle push, and thus providing more power. Further, the fuel used for cooling is ultimately burned downstream of the HPT, providing a bit more power. This method has the advantage of not needing to carry a fluid reservoir.
- (12) **Water Used for Turbine Cooling:** During OEI, water added to the turbine cooling air of the operating engine increases turbine cooling efficiency, enables higher operating temperatures through a throttle push, and thus more power is produced.
- (13) **Turbine Overdesigned By Using Better Material than Required:** The power turbine is made of better materials and single-crystal technology. This enables higher temperatures to be sustained for short duration (short since the entire turbine section is not upgraded). Thus, through a throttle push, more power is produced.
- (14) **Modulated Cooling:** The engine cooling levels are controllable. For two-engine operation, the cooling rates would be nominal. However, with only one engine, the turbine cooling rates would be significantly increased, higher operating temperatures sustained, and contingency power levels generated.
- (15) **Variable Compressor Geometry:** The engine is capable of running two different design points, one would be for OEI hover operation, the other for fuel efficient cruise. Increased core flow during the higher power requirements of OEI operation would be the result.
- (16) **Variable Turbine Geometry:** Same comments as "Variable compressor geometry".
- (17) **Variable Compressor and Turbine Geometry:** Additive effects of both.
- (18) **Water/Methanol Injection:** A water/methanol solution is injected into the compressor or combustor inlet of the remaining operative engine. This enables more power to be produced, especially on low altitude hot days when it would be needed most. This is already a proven means for increasing twin turboprop commuter takeoff performance. The additional system weight would probably be on the order of a passenger. This would have the advantage of high reliability, simple engine modification, and easy on-the-wing functionality checks.

- (19) **Land in Airplane Mode:** Forget the philosophy that one engine should be able to carry the entire vehicle. Glide the tiltrotor down to a landing, rotating the rotors up out of the way just before landing. Accept the resulting dead man's curve and the loss of heliport landing capability. Obviously this is less than desirable if operation is in an urban roof-top to roof-top environment.
- (20) **Autorotate or Other Auxiliary Vertical Landing Modes:** After loss of an engine remaining available power is used to maintain rotor speed and define a steep glide path using wing and rotor lift. Prior to touchdown, the engine is accelerated to contingency power, kinetic energy is transferred to the rotors energy, and the tiltrotor autorotates to a landing - similar to a helicopter.
- (21) **Rocket powered rotor blade backup:** Self contained solid propellant rocket motors on the rotor blade tips to be ignited in the event of an engine failure. Thus, the remaining engine, a steep glide, the higher inertia rotor blades, and this final boost of additional power prior to landing provides a safe touchdown.
- (22) **Variable-speed Gearbox:** Enables the turbine to be oversped to provide additional power for OEI operation.
- (23) **Afterburner transition to Forward Flight:** Same comments as "Land in airplane mode" but now an afterburner assists in the transition from hover to forward flight in case an engine is lost. Obviously though, with the engines mounted on the end of the wings, asymmetric thrust concerns would have to be addressed.

## **5.2 Viable Concepts Selection Methodology**

The concepts developed under Task 2 were then qualitatively evaluated by each individual team member. Each concept was scored on a 5-point scale in each of the following categories:

- Reliability/Safety of the Augmentation System
- Reliability/Safety of the Vehicle/Engine
- Fabrication Cost
- Operating/Maintenance Cost (DOC)
- Environmental Impact
- Power Increase
- Fuel Burn
- Weight
- Complexity

A score of 5 was the best, 1 was the worst. Per individual, the best cumulative score possible was 45, the worst 9. The categories of DOC and fuel burn were then doubled to weight these categories. The weighted scores of all the respondents surveyed were totaled and an overall score for each concept defined.

The proposed concepts fall into three basic categories:

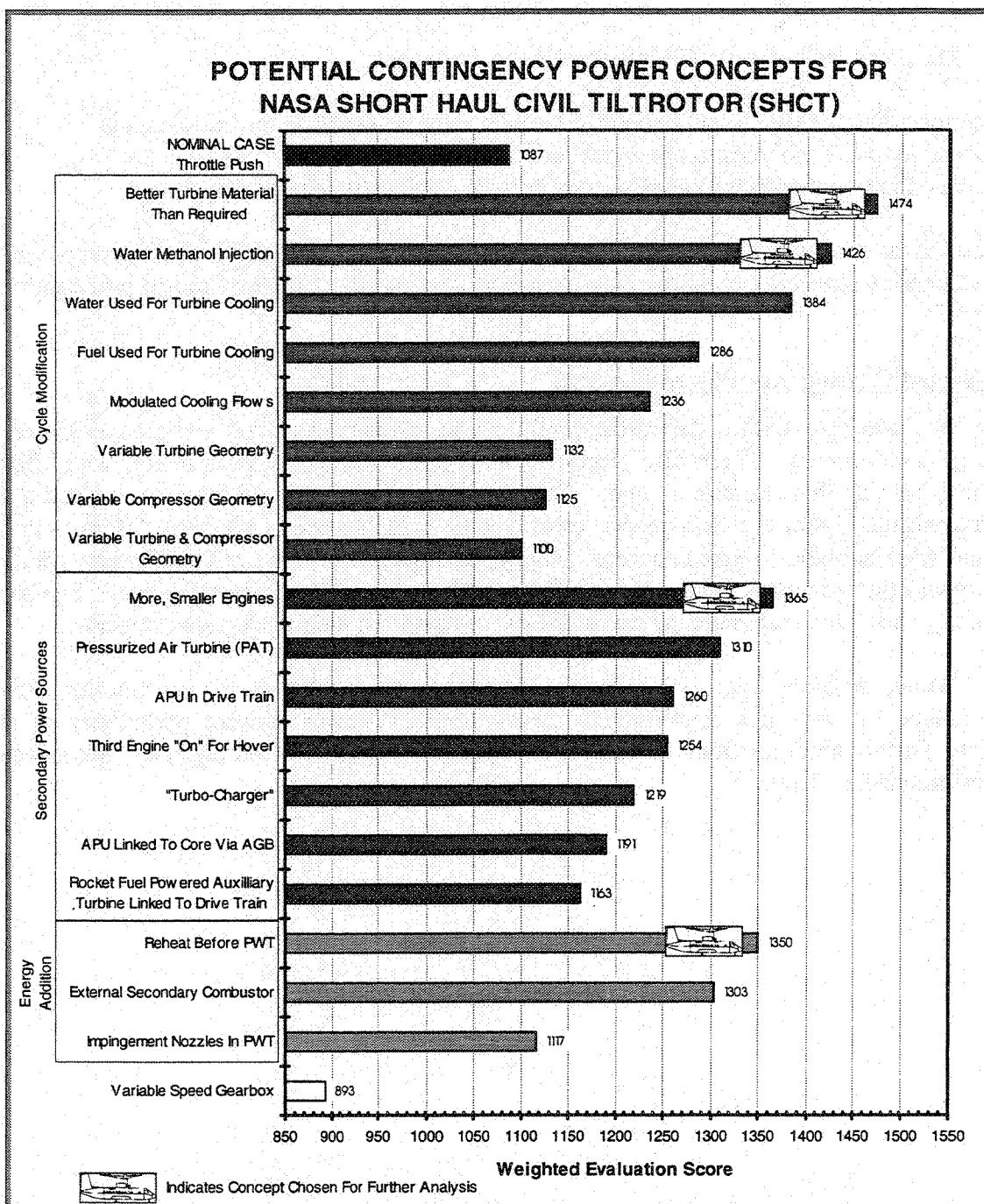
1. Thermodynamic cycle modifications to provide more power from the basic engine
2. Secondary power sources to obtain additional power external to the engine
3. Energy addition methods to generate power from a normally unused component

The individual concepts were ranked within their categories. Then the highest scorers within these categories were chosen as the most viable to go forward. This resulted in four candidate concepts.

### **5.3 Selected Contingency Power Concepts**

Two concepts within the Cycle Modification category received cumulative scores in excess of 1,400 points. These also represent the highest overall. Consequently, both “Better Turbine Material Than Required” and “Water/Methanol Injection” concepts were chosen for further analysis. From the Secondary Power Source category the concept of “More, Smaller Engines” was the highest ranked concept. Finally, the highest concept from the Energy Addition category was the secondary combustor providing “Reheat Before the Power Turbine”. Figure 10 graphically shows the paretoed rankings of the concepts within their respective categories.

“More, Smaller Engines” is more of a systematic solution to the tiltrotor power requirements. It does not contribute to the contingency power concept philosophy of this contract. Furthermore, airframe manufacturer input was negative. Consequently, this concept was not analyzed in detail.



**Figure 10. Potential Contingency Power Concepts for NASA SHCT.**

## **6.0 TASK 3: CONTINGENCY POWER CONCEPT EVALUATION**

Concepts based on “Water/Methanol Injection”, “Better Turbine Material Than Required”, and a secondary combustor providing “Reheat Before the Power Turbine” were thermodynamically modeled and are detailed in the following sections. Engine size was decreased corresponding to the contingency power available, thus driving engine operation from a part power level toward the more efficient design point. These engine operating characteristics were generated and input into VASCOMP to assess the impact of improved fuel efficiency. System size, weight, cost, and performance comparisons with the baseline were made. These concepts are contrasted against the NASA baseline, the AE baseline, and the ideal engine.

### **6.1 NASA Baseline Engine**

NASA baseline engine performance characteristics and features represent the perceived baseline levels attainable. Results were obtained from a VASCOMP output provided by NASA (see Reference 1). Comparisons between the NASA and the AE Baseline engines satisfy the NASA requirement that the contractor define where the model used differed from the NASA provided model (Task Order 48, Task 1 Amendment (e)).

### **6.2 AE Baseline Engine**

Comparisons are benchmarked against the AE Baseline model sized for the tiltrotor application. As detailed in Section 4, Task 1, the AE Baseline has a contingency power level 15 percent greater than takeoff. This rating is obtained through a “throttle push” to operating temperatures higher than the takeoff rating.

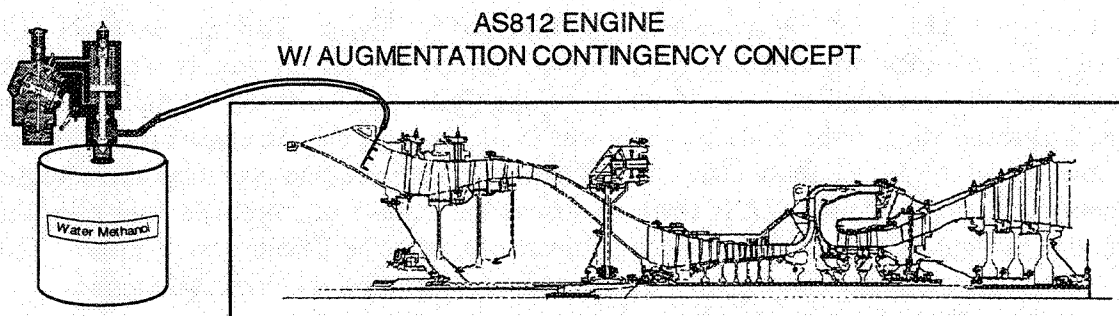
### **6.3 Concept 1: Water/Methanol Injection**

The first concept is a water/methanol injection system, illustrated in Figure 11. Water/methanol injection offers engine power augmentation due to increased mass flow, temperature reduction due to solution evaporation as it passes through the compressor, and methanol combustion in the burner. AE currently offers this enhancement on several regional twin engine turboprop installations for additional takeoff performance.

Based upon an engine sensor (torque or pressure) automatically detecting engine failure, a water/methanol solution is injected into the compressor inlet of the remaining operative engine and accelerated to a contingency temperature rating. A sensitivity study to flow rates was conducted and results are presented for 2000, 4000, and 5000 pph systems. The additional system weight penalty is equivalent to 1 to 2 passengers. This system has the advantages of minimal engine modification, high reliability, low cost, and easy on-the-wing functionality checks.

#### **6.3.1 Sizing**

A 2000 pph augmentation system is predicted to produce a contingency power 26 percent higher than takeoff (CRP/TOP of 1.26). This includes the power increase due to the baseline contingency capability to operate in excess of the takeoff temperature rating. This engine is sized



**Figure 11. Water/Methanol Augmentation Concept.**

to provide 8,520 hp at the sizing point. This produces a nominal sea-level, static, takeoff rating of 7,871 hp with a flow capacity of 42.9 lb/sec.

### **6.3.2 Engine Weight**

Scaling the baseline engine down to this power level results in an engine weighing 905 lb. However, the water/methanol system incurs an additional 209 lb of aircraft system weight. This weight is primarily the fluid for 3 minutes of operation, a single tank, and additional aircraft support structure. Part of this weight also includes the pumps, manifolds, flow pressure switches, valves (metering, control, pressure maintaining, non-return), lines, sensors, and injectors required for each engine.

### **6.3.3 Mission Analysis**

The mission fuel requirements are 1,721 lb for the 200 NM mission, and 4,338 lb for the 600 NM mission. These results actually result in increased fuel requirements over the baseline of 3.6 and 1.4 percent respectively. VASCOMP input defining the engine AEO and OEI operating characteristics are included in Tables II-2 and 3 of Appendix II.

### **6.3.4 Engine Acquisition Cost**

The estimated acquisition cost of this engine is \$1,696,000. Using the dollars per horsepower and dollars per pound trends of the AE Baseline engine, adding in the additional costs to support the CRP rating (control and manufacturing modifications) results in the smaller, less powerful, yet more complex engine costing less than the AE Baseline. There would be an additional airframe cost of \$25,200 for the augmentation system. This extra cost includes the tank, pumps, manifolds, switches, valves, and the aircraft support structure modifications necessary to install an augmentation system. Note: Fluid not included.

### **6.3.5 Engine Direct Maintenance Costs**

The estimated 10-year cumulative engine DMC average cost, based on the 200 and 600 NM missions, would be between \$37.65 to \$48.52 per hour of operation. A more detailed break down is again presented in Appendix III, Tables III-3 and 4.

### 6.3.6 Tiltrotor Direct Operating Costs

The AE engine with a 2000 pph water/methanol injection system resulted in a tiltrotor with a total trip DOC of \$2,068.17 for a 200 NM, or \$4,452.53 with a 600 NM mission range. This translates to \$6.45 to \$8.99 per mile. With 40 revenue paying passengers these cost are 16.12 to 22.46 cents per seat mile. This represents an improvement in DOC of 2.3 to 2.5 percent over the AE Baseline engine.

### 6.3.7 Injection Rate Case Study

A case study was performed to define the sensitivity of injection rate to power benefit. Augmentation system results are summarized in Table 6 for 2000, 4000, and 5000 pph injection rates. VASCOMP input for the 4000 and 5000 pph systems, AEO and OEI, are contained in Appendix II, Tables II-4 through II-7. The power benefit starts to decline rapidly above injection rates 4000 pph. The augmentation systems are estimated to provide average cent/seat mile DOC improvements of 2.4, 3.0, and 3.3 percent respectively.

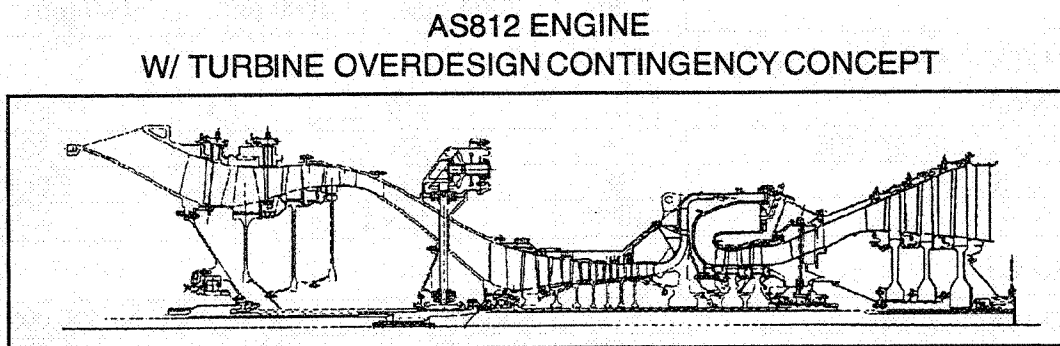
**Table 6. Water/Methanol Augmentation Rate Sensitivities.**

		Units	Concept 1A 2000 pph	Concept 1B 4000 pph	Concept 1C 5000 pph
<b>ENGINE CHARACTERISTICS</b>					
CRP/TOP		—	1.26	1.31	1.32
CRP HP 2K, S, ISA+20C		HP	8,520	8,520	8,520
TOP At SLS, ISA		HP	7,871	7,444	7,286
$W a \sqrt{\theta_2 / \delta_2}$		PPS	42.9	42.9	42.9
<b>COSTS</b>					
Engine Acquisition		1995 \$	\$1,696,000	\$1,605,000	\$1,570,000
Augmentation System		1995 \$	\$25,200	\$30,000	\$33,000
DMC (AE Calc'd)	200 NM	1995 \$	\$48.52	\$47.86	\$47.68
	600 NM	1995 \$	\$37.65	\$37.23	\$37.11
DOC (VASCOMP)	200 NM	1995 \$	\$2,068.17	\$2,054.14	\$2,048.38
	200 NM	1995 \$	\$4,452.53	\$4,423.35	\$4,411.50
<b>WEIGHTS</b>					
Engine Weight		lbs	905	855	835
System Weight		lbs	209	359	434
Mission Block Fuel:	200 NM	lbs	1,721	1,678	1,662
	600 NM	lbs	4,338	4,261	4,220
Total		lbs	5,452	5,475	5,489

## 6.4 Concept 2: Better Turbine Material Than Required

Improved turbine materials and reduced HPT life during contingency operation offers additional engine power augmentation through increased turbine rotor inlet temperatures. This required upgrading the power turbine first-stage ITF/Nozzle 1 from a conventional equiaxed mono-casting to a bi-alloy. The first-stage blades would also change from a directionally solidified alloy to single-crystal 180 material. (Figure 12). This allows the turbine temperature to be increased to 2,850F (plus 200 degrees in deterioration margin). This corresponds to the maximum allowable temperature for the low pressure turbine. This pushes the operating temperatures to the 100 hour life of the high-pressure turbine for the contingency role.

Upon engine failure, identified manually or automatically, the control would enable the turbine to be significantly over-driven for the 2.5-minute OEI event. Because of this short duration, further hot-end section enhancements are not necessary. An on-the-wing hot-section inspection would be required after such an event. While these changes want to drive up the acquisition cost, they are balanced by the smaller engine required. This system has the advantages of basically no engine modification, high reliability, low cost, and easy on-the-wing functionality checks.



**Figure 12. Turbine Overdesign Concept.**

### 6.4.1 Engine Sizing

An oversized turbine system was predicted to produce a contingency power 41 percent higher than takeoff (CRP/TOP of 1.41). This engine was sized to provide 8,884 hp at the design point. This in turn resulted in a nominal sea-level, static, takeoff rating of 7,555 hp. This engine would have a flow capacity of 41.4 pps.

### 6.4.2 Engine Weight

Scaling the baseline engine down to this power level results in an engine weighing 880 lb. With no additional parts relative to the baseline, the engine weight was estimated by scaling the Baseline engine weight based on horsepower and flow levels. A correction was then applied for 2005 technology levels.

### **6.4.3 Mission Analysis**

The mission fuel requirements would be 1,578 lb for the 200 NM mission, and 4,141 lb for the 600 NM mission. These block fuel levels are 5.0 and 3.3 percent lower than required with the AE Baseline engine. VASCOMP input defining the engine operating characteristics for AEO and OEI are included in Table II-8 of Appendix II.

### **6.4.4 Engine Acquisition Costs**

The acquisition cost of an engine at this size class with an oversized turbine would be \$1,683,000. There would be no additional airframe cost. Engine cost was estimated by correlating dollars per horsepower and dollars per pound relative to the AE Baseline engine cost. Then the additional cost of the new turbine design was added.

### **6.4.5 Engine Direct Maintenance Costs**

The estimated 10-year cumulative engine DMC average cost, based on the 200 and 600 NM missions, would be between \$39.12 to \$50.33 per hour of operation. A more detailed breakdown is again presented in Appendix III, Tables III-9 and 10.

### **6.4.6 Tiltrotor Direct Operating Costs**

The AE engine using an improved material power turbine resulted in a tiltrotor with a total trip DOC of \$2,029.86 for a 200 NM, or \$4,376.21 with a 600 NM mission range. This translates to \$6.34 to \$8.82 per mile. With 40 revenue paying passengers these cost are 15.85 to 22.05 cents per seat mile. This represents an improvement in DOC of 3.9 to 4.3% over the AE Baseline engine.

## **6.5 Concept 3: Reheat Before the Power Turbine**

The third concept is the inclusion of a secondary combustor to provide reheat between the high- and low-pressure turbines as shown in Figure 13. Interturbine reheat allows the low-pressure turbine to operate at its temperature limit and not suffer the penalty of running the high-pressure turbine at a life-reducing condition. The length of the interturbine duct in the AS812 baseline engine allowed this concept to be considered. A simple effusion-cooled axial flow combustor can was positioned in front of the power turbine. Proper combustor sizing actually required the power turbine to be pushed back 4 inches. The case between the turbines was resized to maintain proper geometry. An additional cooling circuit was added to cool the first stage nozzles and blades.

In normal operation, the secondary combustor is unlit and results in a 4 percent pressure loss penalty on the operating cycle. When an engine out condition is detected, variable compressor geometry is opened up in the compressor, the secondary combustor is ignited, and cooling is shunted from the HPT to the power turbine. The reheat combustor supplies a mixed low-pressure turbine inlet temperature of 2,300F. This represents a 650-degree increase during an OEI even for additional power augmentation. While variable turbine geometry would further optimize performance during OEI, the added engine complexity/reliability was not cost effective. This concept has the potential to deliver a tremendous amount of additional power and easy on-

the-wing functionality check prior to takeoff. However, the more complex system would require a significant deviation from the original production engine.

### AS812 ENGINE W/ REHEAT CONTINGENCY CONCEPT

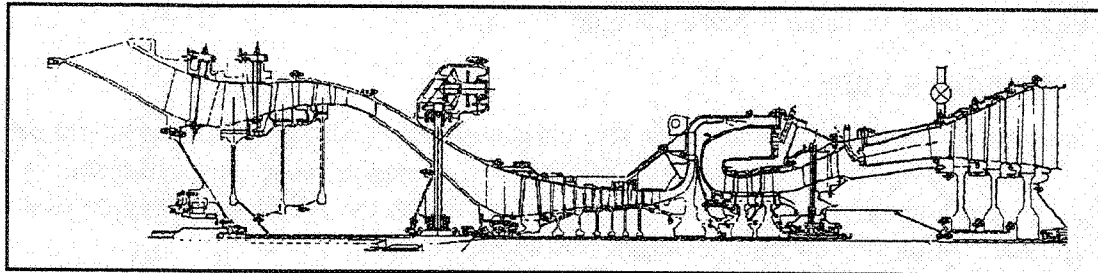


Figure 13. Secondary Combustor Reheat Concept.

#### 6.5.1 Engine Sizing

A secondary combustor system was predicted to produce a contingency power 70 percent higher than takeoff (CRP/TOP of 1.0). This engine was sized to provide 8,927 HP at the design point. This in turn resulted in a nominal sea level, static, takeoff rating of 6,737 HP. This engine would have a core flow capacity of 38.6 lb/sec in normal.

#### 6.5.2 Engine Weight

Scaling the baseline engine down to this takeoff power level results in an engine weighing 850 lb. The engine weight was estimated by scaling the baseline engine weight based on horsepower and flow levels and then adjusting this for the weight of an additional combustor and the longer power shafts. A correction was then applied for 2005 technology levels.

#### 6.5.3 Mission Analysis

The mission fuel requirements would be 1,571 lb for the 200 NM mission, and 4,060 lbs for the 600 NM mission. These block fuel levels are 5.4 and 5.1 percent lower than AE Baseline engine would require on board. VASCOMP input defining the engine operating characteristics for AEO and OEI are included in Tables II-11 and II-12 of Appendix II.

#### 6.5.4 Engine Acquisition Costs

The acquisition cost of this engine would be \$1,626,000. There would be no additional airframe cost. Engine cost was estimated by correlating dollars per horsepower and dollars per pound relative to the baseline engine cost. Then the additional cost of the second combustor and modified control systems were added.

### **6.5.5 Engine Direct Operating Costs**

The estimated ten year cumulative engine DMC average cost, based on the 200 and 600 NM missions, would be between \$42.65 to \$54.49 per hour of operation. A more detailed break down is again presented in Appendix III, Tables III-11 and 12.

### **6.5.6 Tiltrotor Direct Operating Costs**

The AE engine using a secondary combustor for interturbine reheat resulted in a tiltrotor with a total trip DOC of \$1,996.16 for a 200 NM, or \$4,303.74 with a 600 NM mission range. This translates to \$6.23 to \$8.67 per mile. With 40 revenue paying passengers these cost are 15.58 to 21.68 cents per seat mile. This represents an improvement in DOC of 5.6 to 5.9 percent over the AE Baseline engine.

## **6.6 Ideal Engine**

The concept of an ideal engine is introduced for comparison purposes only. The ideal engine represents the entitlement system, and is used to illustrate the efficiency of the technology concepts. The ideal engine is simply one which will never fail. This negates the need for a contingency power level.

The ideal engine was modeled by adjusting the performance characteristics of the AE Baseline engine, though the actual operating characteristics of any engine would have sufficed. The sea-level, static, ISA day maximum power output was changed to occur at the takeoff temperature (contingency was eliminated). Takeoff temperature was defined as the maximum temperature. The normal rated temperature was set 5-degrees lower. VASCOMP empirical weight calculations were accepted, and no propulsion system weight delta was added.

The ideal engine is sized such that half of the maximum vehicle horsepower required is provided by each engine. VASCOMP results indicate a SLS, ISA single engine power rating of 3,678 hp would meet nominal takeoff requirements; 4,800 hp would be necessary for cruise; and 5,714 hp at the design point. The 2K/Static / ISA+20C/HOGE design point still represents the maximum power required, thus the ideal engine was sized at 5,714 hp.

Interestingly, only 26 percent more power would be required from a 5,714 hp engine to meet a SLS, ISA day, OEI takeoff. This differs significantly from the original perception of the ideal case being an engine with a contingency capability that would provide a 100 percent increase in sea-level static power. This kind of increase is only true at the sizing point. Consequently, a statistical analysis to maintain the majority of the takeoff/landing capabilities during OEI may yield a more practical contingency power requirement somewhere between 26 and 100 percent.

## **6.7 System Comparisons**

Comparisons of the power increases due to the contingency concepts, and the impacts on DOC due to being able to use a smaller engine than the baseline, are made in the following

sections. Table 7 shows a comparison of basic engine performance features. Subsequent sections present graphical comparisons of major features of the resulting systems including aircraft weight, engine weight, and operating temperatures.

**Table 7. Engine Performance Comparisons.**

	AE Baseline	Concept 1A	Concept 1B	Concept 1C	Concept 2	Concept 3
<b>SEA LEVEL, STATIC, ISA DAY, TAKEOFF POWER (T4.1=2500F)</b>						
SHP*	9,095	7,871	7,444	7,286	7,555	6,737
SFC	0.366	.381	.380	0.380	0.378	0.382
$W\sqrt{\theta_2/\delta_2}$	47.2	46.4	43.9	42.9	41.4	38.6
OCR	36.6	44.7	44.7	44.7	36.2	40.8
*Note: Interpolated VASCOMP HP Numbers Agree With AE Cycle Models						
<b>25,000 FEET; 350 KTAS; ISA DAY; CRUISE POWER (T4.1=2300F)</b>						
SHP	3,522	3016	2842	2,777	3,147	2,449
SFC	0.361	.372	0.373	0.374	0.353	0.387
$W\sqrt{\theta_2/\delta_2}$	37.6	35.5	33.5	32.8	32.3	29.5
OCR	29.3	35.0	35.0	34.8	28.9	31.1

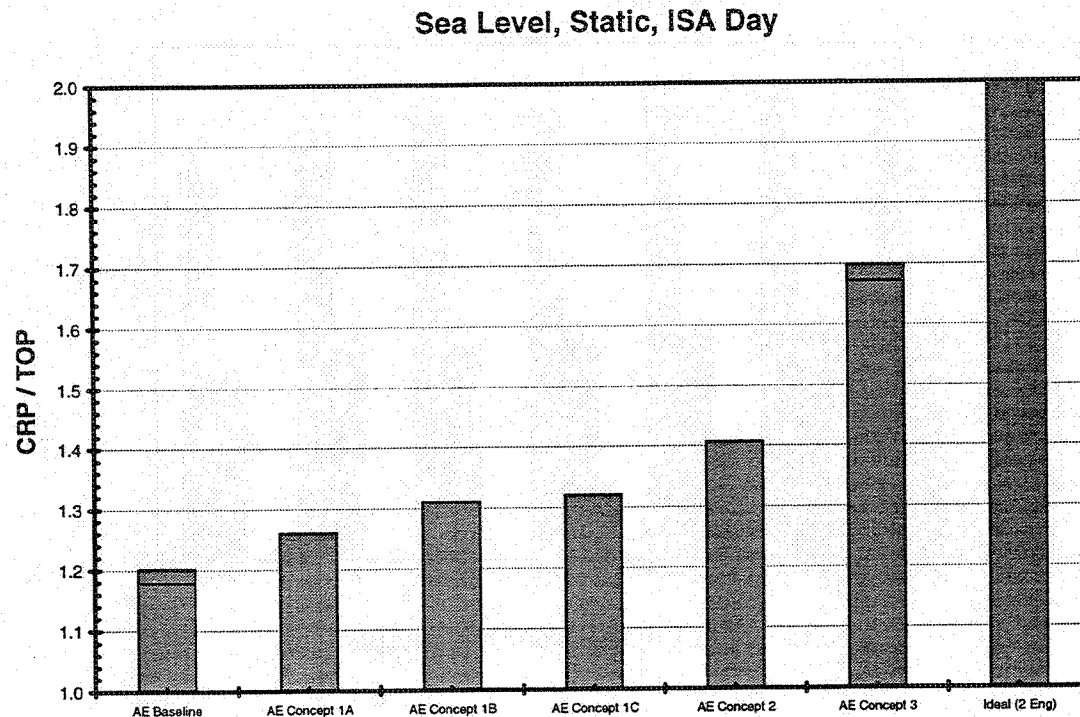
#### **6.7.1 Power Augmentation Ratios, CRP/TOP**

The additional contingency power generated by the proposed concepts is defined by the ratio of contingency to takeoff power (CRP/TOP). Figure 14 presents the ratios for each of the concepts on a sea level, static, ISA day. The AE Baseline engine was used for reference rather than the NASA engine for comparison consistency.

A 1.035 CRP/TOP ratio was quoted for the NASA baseline engine per Reference 1. The AE baseline was nominally set at 1.15 by design. Based on the delta temperature in the thermodynamic engine model the actual ratio was 1.18. VASCOMP interpolation results in a 1.20 ratio. Water/methanol injection would increase the baseline ratios to 1.26, 1.31, and 1.32 for injection rates of 2000, 4000, and 5000 pph, respectively. The turbine over design modification would result in a ratio of 1.41 over the baseline. Adding a secondary combustor to the baseline engine results in a VASCOMP interpolated contingency power level 1.70 times the takeoff rating. Thermodynamic cycle modeling predicted a ratio slightly less, at 1.67. The ideal engine is based on two engines and consequently shows a CRP/TOP ratio of 2.0. Overall, good agreement exists between VASCOMP aircraft model interpolations and AE engine cycle model calculations, validating each other's results.

#### **6.7.2 Vehicle Direct Operating Costs**

To facilitate NASA comparisons, DOC results from VASCOMP have not been adjusted for AE acquisition or DMC numbers. Consequently, DOC numbers are based completely on program VASCOMP calculations and the input sensitivities as specified by NASA.



**Figure 14. CRP/TOP Ratio Comparison of Concepts.**

Figure 15 shows the DOC results, calculated by VASCOMP, for the 200-nm and 600-nm mission profiles. The NASA Baseline engine is presented to compare reference starting points. The ideal engine defines the maximum improvement possible.

Table 8 presents the percent change each concept represents relative to the AE Baseline engine. The ideal engine indicates that at most an 11 percent decrease in DOC could be realized. AE Concept 3, a secondary combustor reheat between the turbines is the best concept on this basis, improving DOC by about 6 percent.

The fuel burned during the mission is a primary driver in operating costs. Figure 16 shows the block fuels required for the 200 NM and the 600 NM mission profiles.

**Table 8. DOC Change Relative to AE Baseline Engine.**

	NASA Baseline	Concept 1A	Concept 1B	Concept 1C	Concept 2	Concept 3	Ideal Engine
<b>200 NM</b>	-1.82%	-2.30%	-2.91%	-3.21%	-3.94%	-5.58%	-10.61%
<b>600 NM</b>	-1.56%	-2.52%	-3.17%	-3.43%	-4.30%	-5.90%	-10.89%

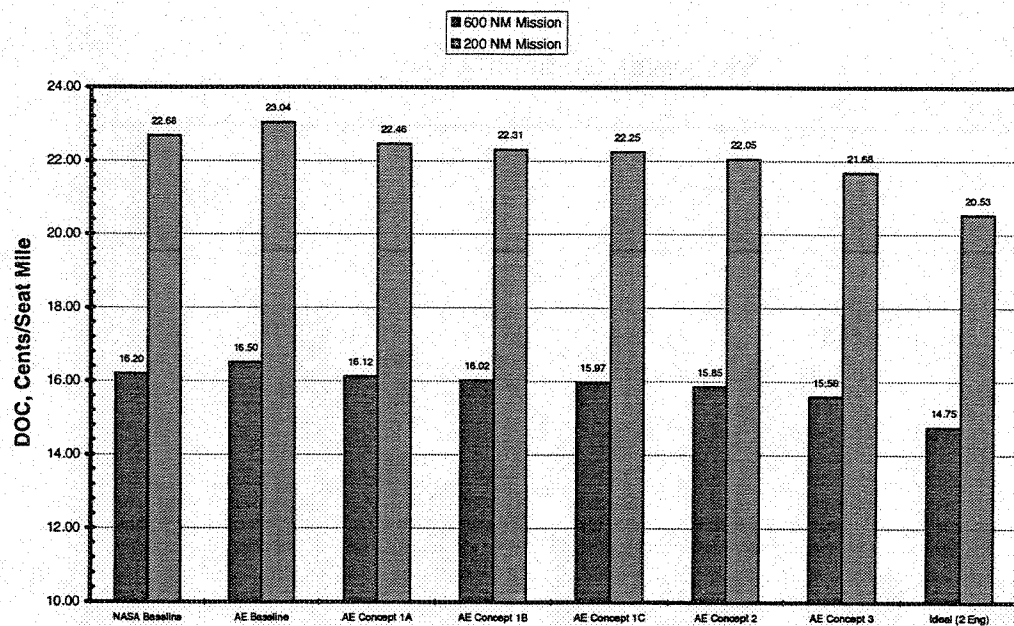


Figure 15. DOC Comparison Of Concepts.

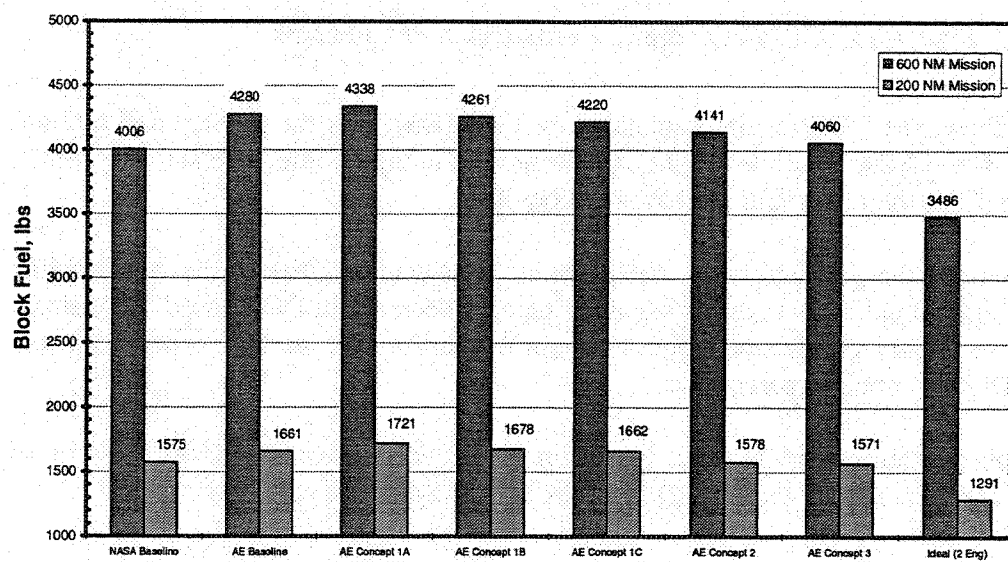


Figure 16. Block Fuel Comparisons With CRP Concepts.

### 6.7.3 Engine Direct Maintenance Costs

AE calculated DMC for the baseline and the individual concept engines independent of program VASCOMP. Detailed DMC tables for each configuration are listed in Appendix III. The cumulative average 10-year cost is shown in Figure 17. Based only on engine DMC, the 5000 pph water/methanol augmentation engine becomes the most cost effective, while the secondary combustor costs exceed that of the AE baseline. This trend is not reflected in the VASCOMP engine maintenance costs, an empirical relationship based on the engine horsepower rating. Vehicle DOC costs should be updated with these engine DMC results to more accurately define the cost tradeoffs.

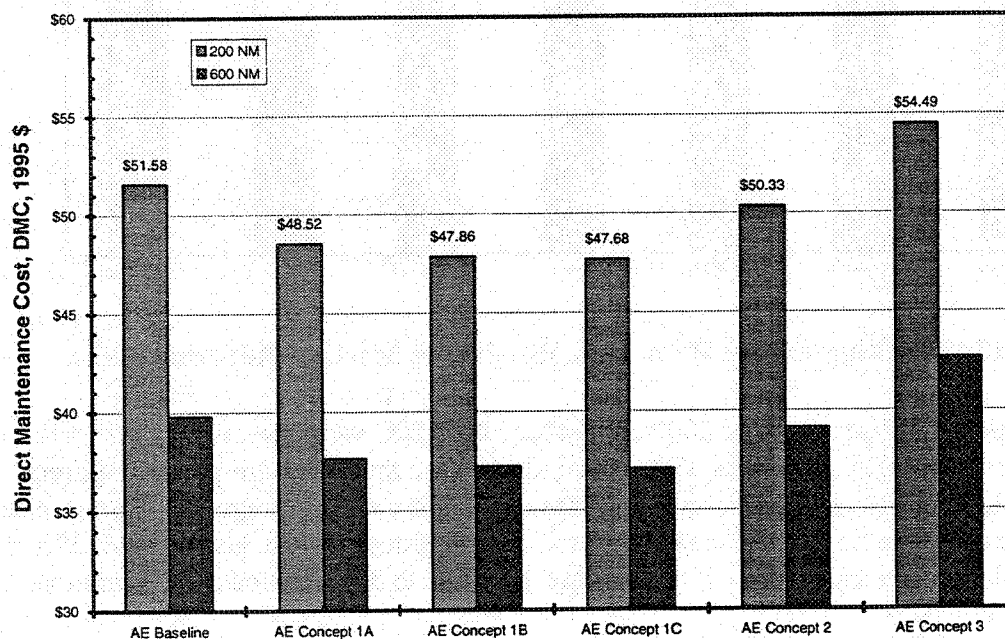
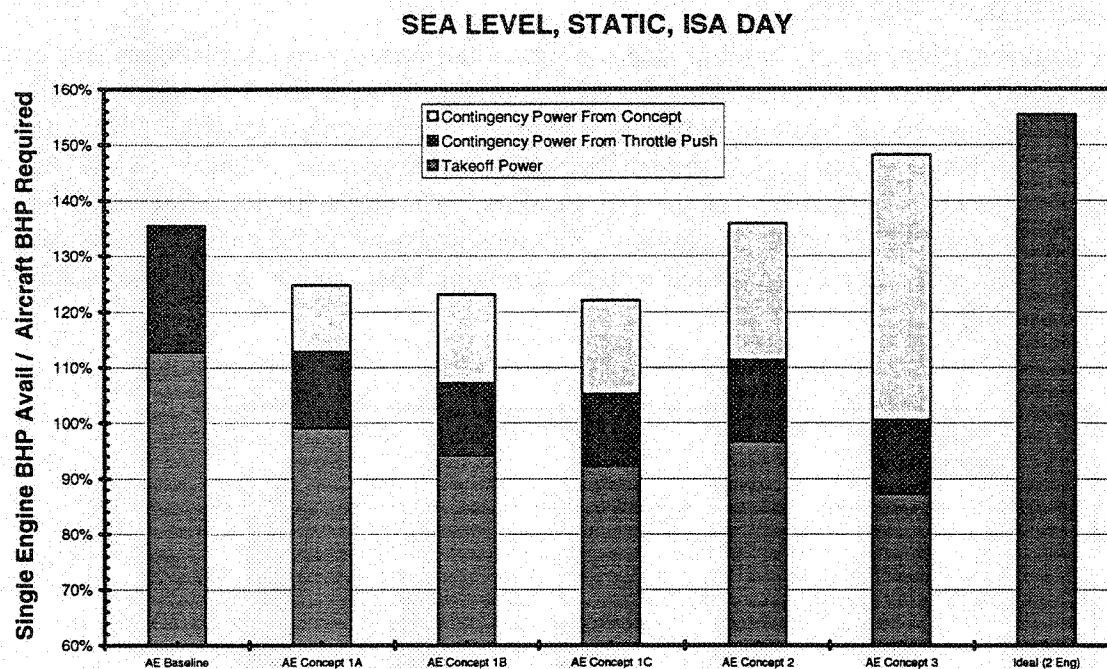


Figure 17. Engine DMC Comparison.

### 6.7.4 Engine Sizings

Figure 18 and Figure 19 show the engine horsepower sizing results at sea level / static / ISA day and 2000 feet / static / ISA+20C day conditions. For comparison purposes different engines were non-dimensionalized by dividing the single-engine power available by the vehicle power required to hover at the specified condition. Further, the stacked bar chart format was used to illustrate what percentage was available based on normal takeoff rating, the nominal throttle push capability of the engine, and then the full contingency capability with the respective technology concepts.

Figure 19 shows that a single engine, with the contingency concept, meets the vehicle power requirements for HOGE at 2000 feet, static, ISA+20C day conditions. Concepts 2 and 3 slightly exceed the vehicle power requirements, indicating perhaps another iteration could further optimize engine sizes to the airframe.



**Figure 18. Resulting Engine HP at SLS, ISA Due to Meeting the Sizing Point.**

HOGF power requirements at 2000 feet, static, ISA+20C were the primary sizing driver. Cruise powers at 25K feet, 350 KTAS, ISA day conditions are the minimum power requirements on an absolute level basis. However, attaining these levels at a cruise temperature rating places the cruise powers as the secondary concern in the sizing process. Sea level, static, ISA day takeoff power levels are easily met if the engine is sized to the previous considerations, as presented in Figure 18.

Table 9 compares the absolute engine horsepower levels. These levels were driven by the resulting tiltrotor weight after VASCOMP sizing with the input engine operating characteristics, weight, and the level of contingency power available. Examining the sizing point horsepower values, it is clear that as the contingency power capability goes up, the nominal engine is resized smaller and smaller as shown by the takeoff ratings.

#### **6.7.5 Resulting Vehicle/Engine Features**

While the engine operating characteristics input to program VASCOMP were fixed and could not be scaled, the vehicle definition was rubberized. Based on NASA-defined aircraft inputs in conjunction with the fixed engine, the tiltrotor weight and drag were empirically derived. The mission profile was used to define the required amount of fuel to be carried on board.

### 2000 FEET, STATIC, ISA+20C DAY

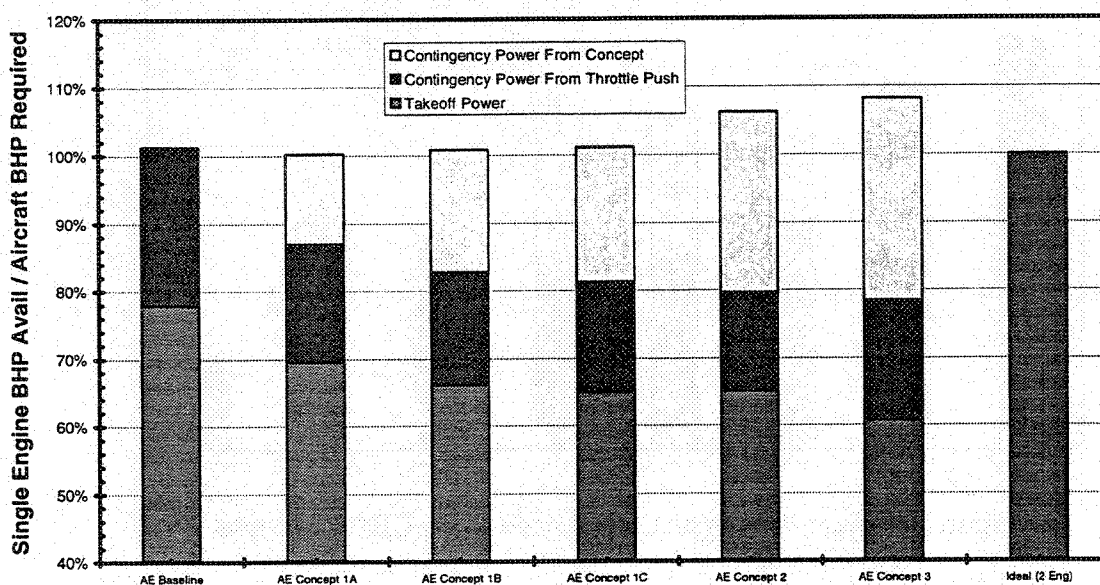


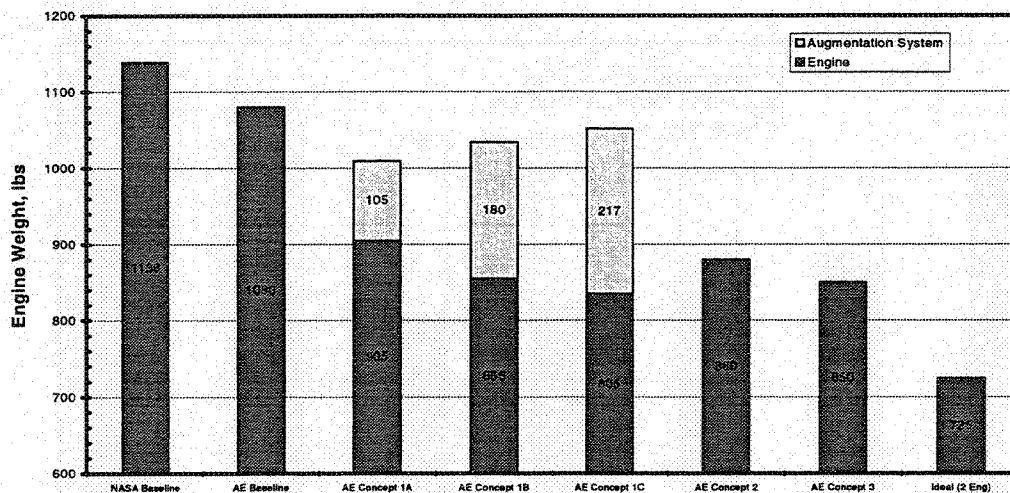
Figure 19. Engines Sized to Provide Required HP at Sizing Point.

Table 9. HOGE Horsepower Levels With CRP Concepts.

	AE Baseline	Concept 1A	Concept 1B	Concept 1C	Concept 2	Concept 3
<b>HOGE, SEA LEVEL, STATIC, ISA DAY</b>						
Vehicle Takeoff Power Required	8063	7941	7904	7881	7814	7718
Single Engine Takeoff Power Available	9095	7871	7444	7286	7555	6737
One Engine Contingency Power Available	10716	9907	9733	9623	8678	11212
<b>HOGE, 2000 FEET, STATIC, ISA+20°C DAY</b>						
Vehicle Takeoff Power Required	8631	8502	8451	8424	8363	8250
Single Engine Takeoff Power Available	6729	5914	5590	5470	5443	5009
One Engine Contingency Power Available	8741	8520	8520	8520	8884	8927

#### 6.7.5.1 Propulsion System Weights

Propulsion system weight and nacelle sizing were direct functions of the maximum sea-level, static, ISA day horsepower capability of the two engines. AE used the VASCOMP propulsion system weight adder to adjust the internal calculation to reflect actual engine weights. Figure 20 compares engine weights. The water/methanol concepts also include half of the augmentation system weight for reference.



**Figure 20. Engine Weight Comparison With CRP Concepts.**

#### **6.7.5.2 Tiltrotor Maximum Takeoff Gross Weights**

The tiltrotor maximum takeoff gross weight (MTOGW) is in turn shown by Figure 21. The effect of the increasing contingency power levels is responsible for driving the vehicle weight down relative to the AE Baseline. As more contingency power is available, the normal engine rating decreases. This results in a smaller, lighter engine. Further, as the engine size decreases, it operates at a higher temperature to produce the same power. This operation is closer to the engine design point and thus more fuel efficient than the bigger baseline engine running at 50 percent power. Consequently, less fuel on board is required. These two effects combine to produce a lighter vehicle.

Although the AE engine is lighter, the vehicle weight with the AE Baseline engine is heavier than that of the NASA Baseline due to fuel consumption levels. The AE Baseline engine requires more fuel to be carried, which in turn requires more structure, and ultimately results in a vehicle 1.3 percent heavier.

#### **6.7.5.3 Takeoff, Climb, And Cruise Powers**

Figure 22 presents the tiltrotor horsepower necessary for takeoff, climb, and cruise on an ISA day starting from the vehicle MTOGW. In general, the horsepower requirements drop as the vehicle weight decreases and engine fuel efficiency increases (thus requiring less fuel to be carried). These results are based on the first point from the respective segments calculated by VASCOMP during the 600-nm mission profile. Takeoff and cruise have been previously defined. Climb occurs after the convert segment and is typically at 1000 feet, 176 KTAS, ISA day conditions.

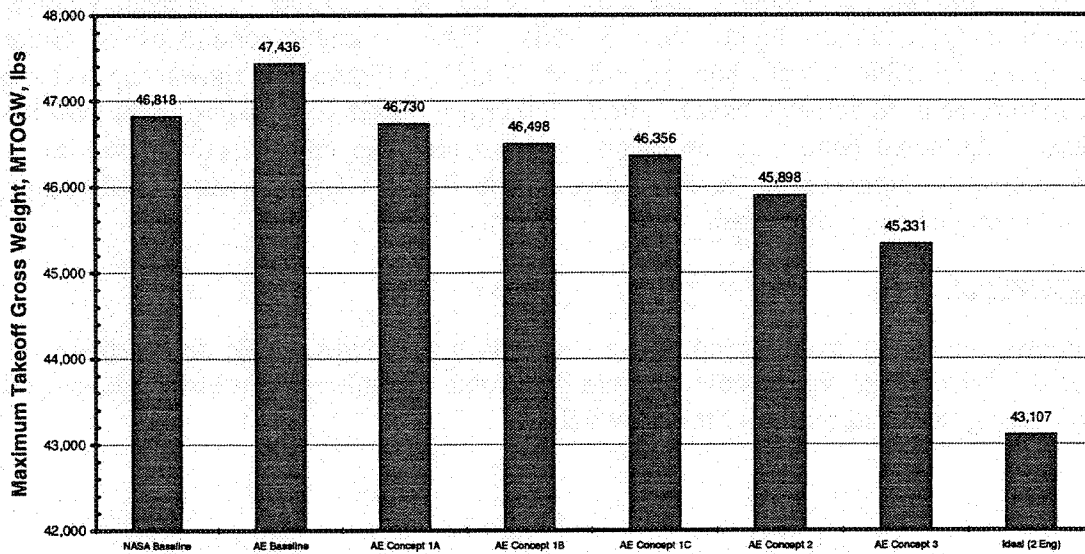


Figure 21. Vehicle Weight Comparison With CRP Concepts.

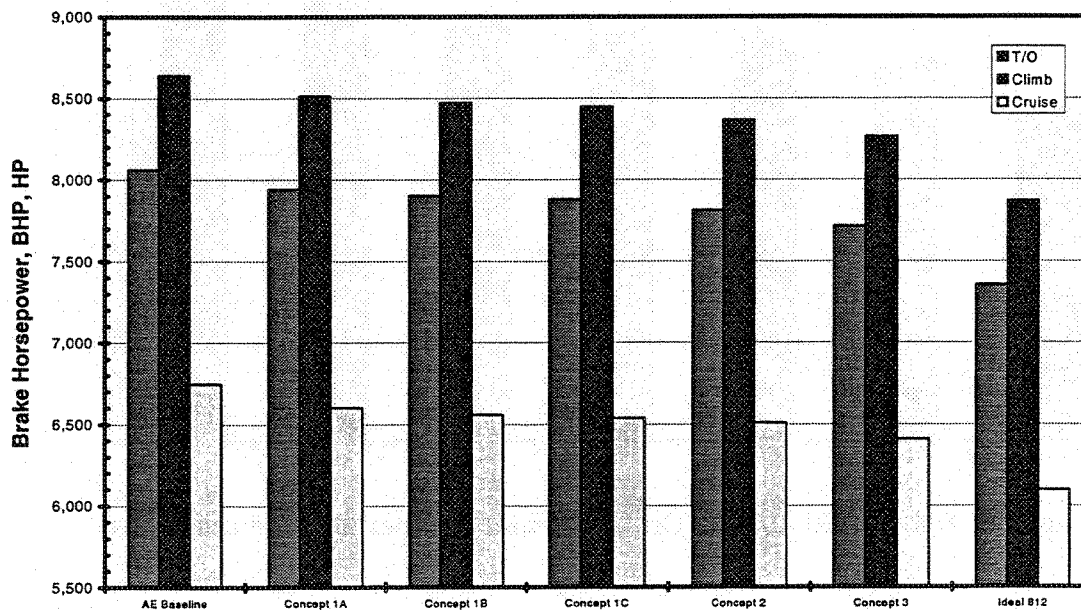


Figure 22. Takeoff, Climb, and Cruise HP Comparisons.

#### 6.7.5.4 Takeoff, Climb, And Cruise Temperatures

The AE engines have a takeoff temperature rating defined at 2960R. Contingency power is limited to a temperature no higher than 3130R. The maximum continuous or cruise temperature rating is 200R lower than takeoff at 2760R. Figure 23 shows the vehicle temperature requirements to achieve takeoff, climb, and cruise power settings during the 600-nm mission profile. As noted before, as the engine gets smaller, the takeoff, climb, and cruise temperatures increase. None of the levels approach the 2960R takeoff or the 2760R cruise ratings due to the engine being oversized.

#### 6.8 New Technology

No improvements, innovations, computer codes or other nonpatentable discoveries were made as a result of the efforts on this contract. No patentable inventions were further developed or discovered during the performance of this contract.

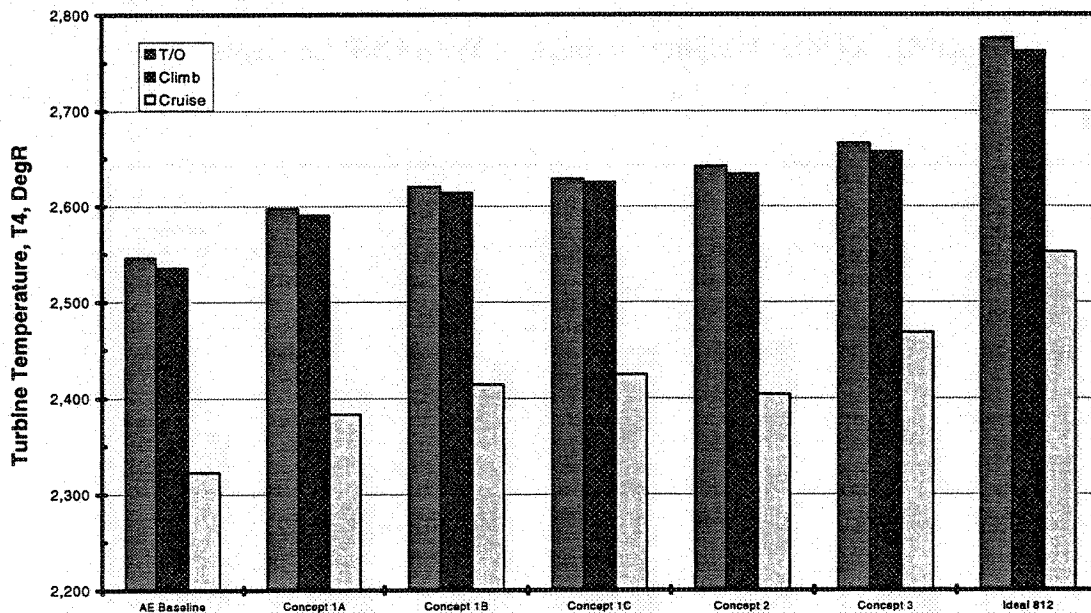


Figure 23. Takeoff, Climb, and Cruise Turbine Temperature Comparisons

## **7.0 TASK 4: CONTINGENCY POWER CONCEPT DEVELOPMENT**

The following sections define the program certification scope and the implementation schedule. Development costs were also predicted.

### **7.1 AS812 Baseline Engine**

Modification of the baseline engine will be limited to the elimination of the reduction gearbox that is used in the turboprop application and changes to the control system to remove propeller controls and facilitate tiltrotor operation.

The reduction gearbox is attached to the inner flange of the inlet housing and provides support for the reduction gearing and bearings. The input shaft for the reduction gearbox is splined and bolted to the LP shaft. When eliminating the gearbox, a new bearing and seal package must be provided for the output shaft and a new shaft will be required.

A program schedule for these modifications is shown in Figure IV-1, Appendix IV. The majority of the changes required are independent of the contingency power concept that is to be developed. However, there may be some efficiencies realized depending on which concept is selected. For example, control system modification will be required for all concepts and the modifications required for the chosen concept should be incorporated at the same time as the change from turboprop to turboshaft controls.

### **7.2 Engine Costs**

In addition to the program development budgets detailed in the following sections, there will also be the expense of the engines required for testing. We estimate that three engines will be required no matter which concept is selected for Phase II. During development and certification phases, engine costs shall be assessed at three times the mature production engine cost which are quoted herein. This higher rate is due to the low number of units initially produced, the need for instrumentation, and for the schedules that have to be expedited to accomplish the required testing. This cost must be added to the budgeted program development costs to define the overall cost to develop the chosen contingency concept.

### **7.3 AS812 With Water Methanol**

The addition of water methanol injection will require minimal hardware modifications so the majority of the cost of developing and qualifying this engine will result from the testing required to ensure the function and reliability of the system, and the power increase and operability of the engine when using water/methanol injection.

#### **7.3.1 Schedule and Budget**

A program schedule for these modifications is shown in Figure IV-2 of Appendix IV. Table IV-1 shows the budget layout for program development of the water/methanol contingency concept.

### **7.3.2 Hardware changes**

The addition of a water/methanol injection system will require the modification or addition of the following hardware listed below:

- Inlet housing
- Water/methanol injectors, lines, sensors, valves, switches, etc.
- Water/methanol tank (assumed to be airframe mounted, with associated airframe support structure added)
- Water/methanol pump

### **7.3.3 Testing**

The water/methanol injection system will require the following tests listed below:

- Performance/Operability
- 150 hour test
- Pump/control durability - rig

## **7.4 Turbine Overdesign Contingency Concept**

Hardware changes are limited to replacing the LPT materials with upgraded (higher stress rupture strength) material and introduction of a bi-alloy first LP nozzle. Cycle testing, designed to inflict the maximum thermal stresses on the turbine components, will be performed to qualify this contingency power concept.

### **7.4.1 Schedule and Budget**

A program schedule for these modifications is shown in Figure IV-3 of Appendix IV. Table IV-2 shows the budget layout for program development of the over designed turbine contingency concept.

### **7.4.2 Hardware Changes**

The overdesigned turbine concept will require:

- New, bi-alloy cast first-stage LPT nozzles
- First-stage LPT blade material changed to single-crystal 180 material

### **7.4.3 Testing**

As a consequence of the limited changes relative to the baseline production engine, the qualification testing can be limited to a single 1000 cycle endurance test.

## **7.5 Secondary Combustor**

The secondary combustor system is the most complex modification of the proposed concepts. It requires the design and testing of the additional combustor, fuel injectors, and additional control systems, modification of the inter-turbine duct, and the addition of a turbine cooling circuit.

### **7.5.1 Schedule and Budget**

A program schedule for these modifications is shown in Figure IV-4 of Appendix IV. Table IV-3 shows the budget layout for program development of the secondary combustor contingency concept.

### **7.5.2 Hardware Modifications**

The addition of the secondary combustor will require major changes to the engine configuration and will result in a large amount of work to redesign and re-analyze existing components for the impact of the changes. Areas affected are:

- Interturbine Duct - lengthened to accommodate the combustor and features added to accommodate fuel nozzles and manifolds.
- LPT Shaft - lengthened due to the increased length inter-turbine duct. This will require re-analysis to shaft dynamics. Bearing stiffnesses need to be re-evaluated as part of this study. Bearing housing stiffnesses may have to be adjusted.
- Secondary cooling - an automatic control system reduces cooling air to the HP turbine and introduces it to the LP turbine when this combustor is operated.

### **7.5.3 Testing**

Due to the many changes relative to the baseline production engine, qualification testing would require a larger scope than the other concepts, consisting of the following tests:

- Combustor rig
- Emissions
- Over-temperature/Over-torque
- 150 hour
- 1000-Cycle Test
- Performance/Operability

## 8.0 REFERENCES

- 1     **“A REVISED SH(CT) MISSION AND CONFIGURATION BASELINE”,** NASA MEMORANDUM from the Advanced Tiltrotor Transport Technology (ATTT) Project Office, Karen Studebaker, April 12, 1995
- 2     **“USER’S MANUAL FOR VASCOMP II, THE V/STOL AIRCRAFT SIZING AND PERFORMANCE COMPUTER PROGRAM”;** Boeing VERTOL Company; A.H. Schoen, H. Rosenstein, K.A. Stanzione, and J.S. Wisniewski; 1980; Volumes 1 and 2; D8-0375-VOL-6-REV-3
- 3     **“UNABRIDGED GLOSSARY OF VASCOMP II - INCLUDING NASA MODIFICATIONS”,** NASA Addendum To VASCOMP Users Manual, Courtesy Of Jim Phillips and Karen Studebaker, Version 1.14, June 13, 1995

## **APPENDIX I**

### **Propulsion System Sizing Example**

**(3 Pages)**

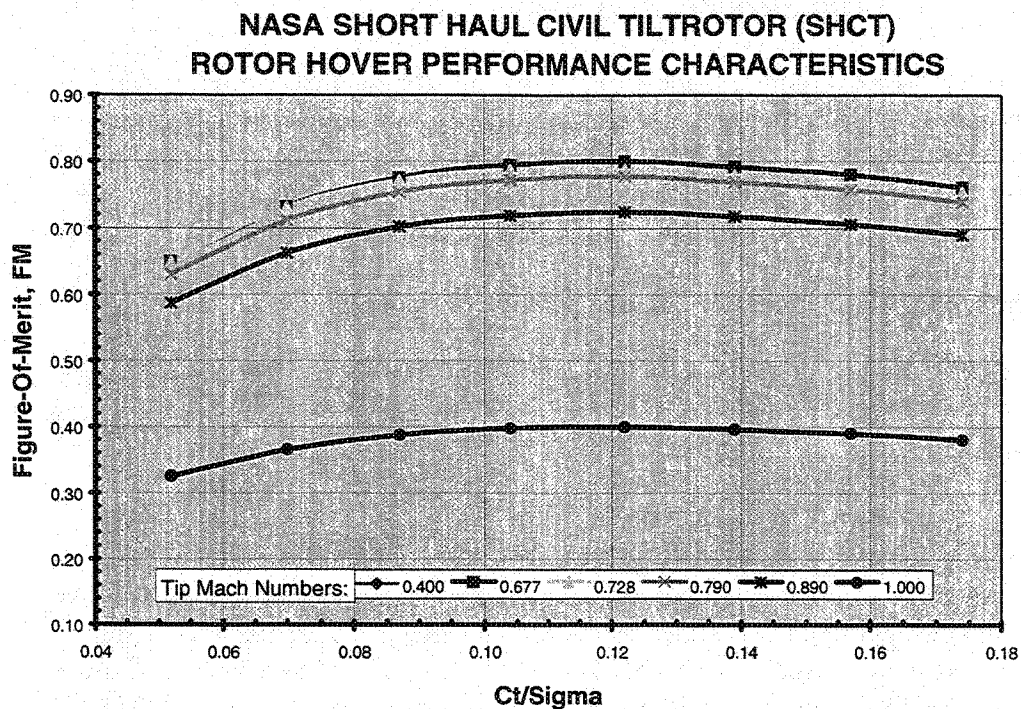


## Propulsion System Sizing Example

In general, Task 1 required choosing/sizing an engine that would power the tiltrotor defined by NASA during OEI operation at the design point. Emergency power levels implied by an OEI event were limited to a throttle push producing no more than 15 percent additional power above the normal takeoff rating. Consequently, a single engine was required that would provide the power for a vehicle around 46,000 pounds the ability to hover out of ground effect (HOGE), at 2000 feet, on an ISA+20° Celsius (C) day. Power in excess of the sizing point for climb capability was not required.

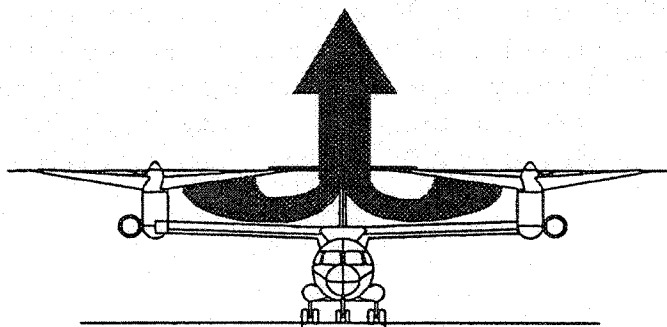
The AS812 engine was sized to provide 8,741 HP at the 2000 foot, static, ISA+20C, CRP, OEI sizing point. Inputs necessary to calculate the tiltrotor power required include:

- (1) Tiltrotor weight (W): Program VASCOMP sizes the vehicle and defines its Maximum TakeOff Gross Weight (MTOGW). This was an iterative process as engine weight is a function of the sea level contingency horsepower rating. An input engine weight delta was added to the VASCOMP calculated engine weight in order to obtain the actual weight of the AS812 engine. However, the tiltrotor weight was MTOGW less any fuel used prior to the hover (i.e., for taxi). MTOGW was 47,436 lb, about 47 lb of fuel were burned during the taxi segment, for a takeoff hover weight of 47,389 lb.
- (2) Transmission efficiency ( $\eta_{\text{Tran}}$ ), or the ratio power delivered to the rotors to engine brake horsepower: NASA input specified this as a constant 0.9809.
- (3) Power extracted from the engines ( $P_{\text{acc}}$ , hp): Again, NASA input specified this as a constant 437.3 hp. This value includes power for the environmental control system, air particle separator, transmission blower and windage, hydraulic, and electrical components.
- (4) Figure-of-Merit (FM), or the rotor hover performance characteristics: These are shown graphically in Figure I- 1 and are based on the results of concurrent industry proprotor studies by Sikorsky, MDHS, Boeing, and Bell. The FM achieves its design optimum of 0.800 on a typical SLS, ISA day with MTOGW and takeoff power. It drops to approximately 0.7901 at the OEI design point conditions, CRP.



**Figure I- 1. Rotor Performance Characteristics.**

- (5) Thrust-to-weight ratio (T/W): Program VASCOMP calculates a hover download (DL/W) force due to the rotor wash meeting in the center of the wing and producing a downward force due to the “fountain effect”, see Figure I- 2. This force is typically about 10% of the vehicle weight (9.75% during a normal SL, static, ISA day, AEO, hover; 9.59 percent during the 2K, static, ISA+20C, CRP, OEI hover). The T/W in hover is the sum of the vehicle weight and the download.



**Figure I- 2. Illustration of Rotor Download Force.**

- (6) Rotor radius (r, feet): Program VASCOMP sizes the rotor during vehicle sizing calculations. The tiltrotor has a rotor with a diameter of 41.8 feet with the AE AS812 baseline engine.

- (7) Number of rotors (No): The tiltrotor configuration specifies 2 rotors.
- (8) Density ( $\rho$ , slugs/cubic foot): The 2K design point results in a density of 2.09371E-03 slugs/cubic foot per an International Standard Atmosphere.

With these inputs a horsepower required of 8,678 can be back calculated from the definition of Figure-of-Merit:

$$BHP = \frac{1}{\eta_{tran}} \cdot \left[ \frac{1}{\sqrt{2}} \cdot \frac{W \cdot \left( \frac{T}{W} \right)}{FM \cdot 550} \cdot \sqrt{\frac{W \cdot \left( \frac{T}{W} \right)}{\rho \cdot No \cdot (\pi r^2)}} \right] + P_{acc}$$

VASCOMP results at this condition were within 0.5 percent, validating the sizing level. The AE cycle model at its contingency temperature rating resulted in a horsepower output of 8,741 meeting the vehicle power requirements.



**APPENDIX II**

**VASCOMP Input Defining  
Engine Operating Characteristics**

**(10 Pages)**



```

TSHP=1460., 1835., 1935., 2110., 2260.,
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SHPAV= 0.0015, 0.0021, 0.0214, 0.0366, 0.0486, 0.0605, , , , , ,
      0.0047, 0.0093, 0.0154, 0.0348, 0.0596, 0.0928, , , , , ,
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      0.1543, 0.1660, 0.1970, 0.2234, 0.2671, 0.3207, , , , , ,
      0.3012, 0.3198, 0.3672, 0.4070, 0.4586, 0.5237, , , , , ,
      0.5971, 0.6291, 0.7136, 0.7796, 0.8659, 0.9752, , , , , ,
      0.8487, 0.8889, 1.0080, 1.0958, 1.2104, 1.3556, , , , , ,
      1.0000, 1.0440, 1.1790, 1.2767, 1.4040, 1.5649, , , , , ,
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      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , , ,
      0.8991, 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, , , , , ,
      0.9585, 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,

TN2= 1460., 1835., 1935., 2110., 2260.,
      2460., 2760., 2960., 3110., 3960.,
AM2 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , ,
ATWO= 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , ,

```

Table II- 1. AE BASELINE ENGINE VASCOMP INPUT.

```

TSHP=1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AMSH= 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
SHPAV= 0.0015, 0.0021, 0.0214, 0.0366, 0.0486, 0.0605, , , , ,
      0.0298, 0.0341, 0.0556, 0.0810, 0.1119, 0.1514, , , , ,
      0.0574, 0.0634, 0.0863, 0.1123, 0.1464, 0.1893, , , , ,
      0.1655, 0.1761, 0.2063, 0.2366, 0.2801, 0.3352, , , , ,
      0.3132, 0.3309, 0.3772, 0.4168, 0.4674, 0.5340, , , , ,
      0.4563, 0.4817, 0.5437, 0.5949, 0.6609, 0.7455, , , , ,
      0.6270, 0.6593, 0.7413, 0.8074, 0.8921, 0.9997, , , , ,
      0.8790, 0.9202, 1.0357, 1.1231, 1.2352, 1.3797, , , , ,
      1.0000, 1.0446, 1.1741, 1.2706, 1.3956, 1.5529, , , , ,
      1.4769, 1.5377, 1.7262, 1.8753, 2.0455, 2.2707, , , , ,

TWD= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AMWD = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
WDOT= 0.0405, 0.0435, 0.0474, 0.0531, 0.0603, 0.0792, , , , ,
      0.0786, 0.0810, 0.0884, 0.0945, 0.1023, 0.1117, , , , ,
      0.0864, 0.0890, 0.0972, 0.1036, 0.1118, 0.1219, , , , ,
      0.1127, 0.1159, 0.1262, 0.1341, 0.1444, 0.1570, , , , ,
      0.1582, 0.1628, 0.1772, 0.1886, 0.2031, 0.2210, , , , ,
      0.2028, 0.2085, 0.2267, 0.2409, 0.2592, 0.2822, , , , ,
      0.2542, 0.2614, 0.2839, 0.3016, 0.3244, 0.3528, , , , ,
      0.3345, 0.3438, 0.3732, 0.3963, 0.4260, 0.4630, , , , ,
      0.3713, 0.3817, 0.4142, 0.4399, 0.4726, 0.5136, , , , ,
      0.5535, 0.5693, 0.6179, 0.6565, 0.7059, 0.7675, , , , ,

TN1= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AM1 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
AONE= 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8991, 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, , , , ,
      0.9294, 0.9294, 0.9294, 0.9294, 0.9294, 0.9294, , , , ,
      0.9585, 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

TN2= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AM2 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
ATWO= 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

```

Table II-2. CONCEPT 1A: 2000 PPH WATER/METHANOL SYSTEM "AEO".



```

TSHP=1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AMSHP= 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
SHPAV= 0.0015, 0.0021, 0.0214, 0.0366, 0.0486, 0.0605, , , , ,
      0.0288, 0.0328, 0.0563, 0.0821, 0.1133, 0.1536, , , , ,
      0.0563, 0.0621, 0.0875, 0.1137, 0.1482, 0.1917, , , , ,
      0.1645, 0.1749, 0.2041, 0.2386, 0.2825, 0.3385, , , , ,
      0.3120, 0.3294, 0.3756, 0.4150, 0.4655, 0.5410, , , , ,
      0.4551, 0.4799, 0.5419, 0.5930, 0.6590, 0.7434, , , , ,
      0.6264, 0.6587, 0.7392, 0.8053, 0.8900, 0.9975, , , , ,
      0.8789, 0.9203, 1.0335, 1.1209, 1.2328, 1.3750, , , , ,
      1.0000, 1.0446, 1.1718, 1.2681, 1.3930, 1.5503, , , , ,
      1.4791, 1.5399, 1.7290, 1.8786, 2.0452, 2.2704, , , , ,

TWD= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AMWD = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
WDOT= 0.0405, 0.0435, 0.0474, 0.0531, 0.0603, 0.0792, , , , ,
      0.0785, 0.0809, 0.0884, 0.0946, 0.1022, 0.1116, , , , ,
      0.0863, 0.0889, 0.0970, 0.1035, 0.1118, 0.1219, , , , ,
      0.1126, 0.1158, 0.1261, 0.1340, 0.1443, 0.1569, , , , ,
      0.1581, 0.1627, 0.1771, 0.1884, 0.2030, 0.2209, , , , ,
      0.2025, 0.2084, 0.2266, 0.2407, 0.2590, 0.2818, , , , ,
      0.2541, 0.2613, 0.2837, 0.3011, 0.3241, 0.3525, , , , ,
      0.3342, 0.3437, 0.3730, 0.3961, 0.4257, 0.4627, , , , ,
      0.3710, 0.3815, 0.4139, 0.4394, 0.4723, 0.5131, , , , ,
      0.5534, 0.5690, 0.6178, 0.6563, 0.7055, 0.7672, , , , ,

TN1= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AM1 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
AONE= 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8991, 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, , , , ,
      0.9294, 0.9294, 0.9294, 0.9294, 0.9294, 0.9294, , , , ,
      0.9585, 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

TN2= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AM2 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
ATWO= 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

```

Table II- 4. CONCEPT 1B: 4000 PPH WATER/METHANOL SYSTEM "AEO".

```

TSHP=1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AMSHP= 0.0, 0.0002, 0.0004, , , , , , , ,
SHPAV= 0.014585, 0.014585, 0.014585, , , , , , , ,
      0.291690, 0.291690, 0.291690, , , , , , , ,
      0.616090, 0.616090, 0.616090, , , , , , , ,
      0.713806, 0.713806, 0.713806, , , , , , , ,
      0.928928, 0.928928, 0.928928, , , , , , , ,
      1.041749, 1.041749, 1.041749, , , , , , , ,
      1.396256, 1.396256, 1.396256, , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,

```

```

TWD= 1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AMWD = 0.0, 0.0002, 0.0004, , , , , , , ,
WDOT= 0.0055, 0.0055, 0.0055, , , , , , , ,
      0.1090, 0.1090, 0.1090, , , , , , , ,
      0.2086, 0.2086, 0.2086, , , , , , , ,
      0.2346, 0.2346, 0.2346, , , , , , , ,
      0.3001, 0.3001, 0.3001, , , , , , , ,
      0.3345, 0.3345, 0.3345, , , , , , , ,
      0.4934, 0.4934, 0.4934, , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,

```

```

TN1= 1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AM1 = 0.0, 0.0002, 0.0004, , , , , , , ,
AONE= 0.5000, 0.5000, 0.5000, , , , , , , ,
      0.7007, 0.7007, 0.7007, , , , , , , ,
      0.9475, 0.9475, 0.9475, , , , , , , ,
      0.9585, 0.9585, 0.9585, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,

```

```

TN2= 1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AM2 = 0.0, 0.0002, 0.0004, , , , , , , ,
ATWO= 1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,
      , , , , , , , ,

```

**Table II- 5. CONCEPT 1B: 4000 PPH WATER/METHANOL SYSTEM "OEI".**

```

TSHP=1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AMSHP= 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
SHPAV= 0.0015, 0.0021, 0.0214, 0.0366, 0.0486, 0.0605, , , , ,
      0.0283, 0.0323, 0.0567, 0.0825, 0.1138, 0.1543, , , , ,
      0.0559, 0.0616, 0.0878, 0.1140, 0.1489, 0.1925, , , , ,
      0.1641, 0.1743, 0.2046, 0.2393, 0.2834, 0.3397, , , , ,
      0.3117, 0.3287, 0.3749, 0.4144, 0.4677, 0.5434, , , , ,
      0.4549, 0.4794, 0.5413, 0.5923, 0.6583, 0.7427, , , , ,
      0.6262, 0.6585, 0.7408, 0.8407, 0.9284, 1.0396, , , , ,
      0.8789, 0.9203, 1.0325, 1.1200, 1.2320, 1.3741, , , , ,
      1.0000, 1.0446, 1.1710, 1.2671, 1.3922, 1.5493, , , , ,
      1.4794, 1.5403, 1.7296, 1.8792, 2.0443, 2.2695, , , , ,

TWD= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AMWD = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
WDOT= 0.0405, 0.0435, 0.0474, 0.0531, 0.0603, 0.0792, , , , ,
      0.0785, 0.0808, 0.0884, 0.0944, 0.1022, 0.1116, , , , ,
      0.0863, 0.0889, 0.0971, 0.1036, 0.1118, 0.1220, , , , ,
      0.1125, 0.1158, 0.1261, 0.1340, 0.1442, 0.1569, , , , ,
      0.1580, 0.1627, 0.1771, 0.1884, 0.2029, 0.2209, , , , ,
      0.2025, 0.2083, 0.2264, 0.2407, 0.2590, 0.2819, , , , ,
      0.2539, 0.2612, 0.2837, 0.3014, 0.3242, 0.3526, , , , ,
      0.3341, 0.3434, 0.3727, 0.3960, 0.4256, 0.4625, , , , ,
      0.3709, 0.3813, 0.4138, 0.4393, 0.4721, 0.5130, , , , ,
      0.5531, 0.5689, 0.6176, 0.6561, 0.7054, 0.7671, , , , ,

TN1= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AM1 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
AONE= 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8991, 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, , , , ,
      0.9294, 0.9294, 0.9294, 0.9294, 0.9294, 0.9294, , , , ,
      0.9585, 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

TN2= 1460., 2060., 2110., 2260., 2460.,
      2610., 2760., 2960., 3110., 3860.,
AM2 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , ,
ATWO= 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

```

Table II- 6. CONCEPT 1C: 5000 PPH WATER/METHANOL SYSTEM "AEO".

```

TSHP=1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AMSHP= 0.0, 0.0002, 0.0004, , , , , , ,
SHPAV= 0.016680, 0.016680, 0.016680, , , , , , ,
      0.333608, 0.333608, 0.333608, , , , , , ,
      0.664710, 0.664710, 0.664710, , , , , , ,
      0.751297, 0.751297, 0.751297, , , , , , ,
      0.938156, 0.938156, 0.938156, , , , , , ,
      1.044484, 1.044484, 1.044484, , , , , , ,
      1.373392, 1.373392, 1.373392, , , , , , ,
      , , , , , , ,
      , , , , , , ,
      , , , , , , ,

```

```

TWD= 1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AMWD = 0.0, 0.0002, 0.0004, , , , , , ,
WDOT= 0.0059, 0.0059, 0.0059, , , , , , ,
      0.1174, 0.1174, 0.1174, , , , , , ,
      0.2137, 0.2137, 0.2137, , , , , , ,
      0.2380, 0.2380, 0.2380, , , , , , ,
      0.2954, 0.2954, 0.2954, , , , , , ,
      0.3292, 0.3292, 0.3292, , , , , , ,
      0.5868, 0.5868, 0.5868, , , , , , ,
      , , , , , , ,
      , , , , , , ,
      , , , , , , ,

```

```

TN1= 1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AM1 = 0.0, 0.0002, 0.0004, , , , , , ,
AONE= 0.5000, 0.5000, 0.5000, , , , , , ,
      0.7007, 0.7007, 0.7007, , , , , , ,
      0.9475, 0.9475, 0.9475, , , , , , ,
      0.9585, 0.9585, 0.9585, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      , , , , , , ,
      , , , , , , ,
      , , , , , , ,

```

```

TN2= 1000., 2160., 2660., 2760., 2960.,
      3110., 3860.,
AM2 = 0.0, 0.0002, 0.0004, , , , , , ,
ATWO= 1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      1.0000, 1.0000, 1.0000, , , , , , ,
      , , , , , , ,
      , , , , , , ,
      , , , , , , ,

```

Table II- 7. CONCEPT 1C: 5000 PPH WATER/METHANOL SYSTEM "OEI".

TSHP=1460., 1935., 2060., 2260., 2460.,  
 2760., 2960., 3160., 3310., 4060.,  
 AMSHP= 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , , ,  
 SHPAV= 0.0015, 0.0021, 0.0214, 0.0366, 0.0486, 0.0605, , , , , , ,  
 0.0112, 0.0149, 0.0301, 0.0424, 0.0599, 0.0803, , , , , , ,  
 0.0278, 0.0317, 0.0602, 0.0842, 0.1203, 0.1573, , , , , , ,  
 0.1243, 0.1331, 0.1685, 0.2088, 0.2511, 0.3034, , , , , , ,  
 0.2706, 0.2860, 0.3294, 0.3666, 0.4213, 0.4924, , , , , , ,  
 0.5903, 0.6215, 0.6996, 0.7645, 0.8484, 0.9555, , , , , , ,  
 0.8706, 0.9111, 1.0267, 1.1159, 1.2314, 1.3779, , , , , , ,  
 1.0958, 1.1437, 1.2808, 1.3852, 1.5212, 1.6931, , , , , , ,  
 1.2237, 1.2752, 1.4267, 1.5413, 1.6901, 1.8779, , , , , , ,  
 1.7471, 1.8153, 2.0282, 2.1965, 2.3941, 2.6514, , , , , , ,

TWD= 1460., 1935., 2060., 2260., 2460.,  
 2760., 2960., 3160., 3310., 4060.,  
 AMWD = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , , ,  
 WDOT= 0.0305, 0.0335, 0.0424, 0.0451, 0.0478, 0.0522, , , , , , ,  
 0.0381, 0.0395, 0.0433, 0.0464, 0.0502, 0.0551, , , , , , ,  
 0.0742, 0.0765, 0.0840, 0.0899, 0.0978, 0.1066, , , , , , ,  
 0.1003, 0.1033, 0.1134, 0.1226, 0.1324, 0.1443, , , , , , ,  
 0.1449, 0.1492, 0.1626, 0.1733, 0.1868, 0.2036, , , , , , ,  
 0.2420, 0.2490, 0.2710, 0.2883, 0.3107, 0.3387, , , , , , ,  
 0.3289, 0.3383, 0.3682, 0.3917, 0.4218, 0.4593, , , , , , ,  
 0.3886, 0.3995, 0.4337, 0.4607, 0.4953, 0.5384, , , , , , ,  
 0.4274, 0.4394, 0.4768, 0.5063, 0.5443, 0.5914, , , , , , ,  
 0.6226, 0.6400, 0.6943, 0.7372, 0.7920, 0.8605, , , , , , ,

TN1= 1460., 1960., 2060., 2260., 2460.,  
 2760., 2960., 3160., 3310., 4060.,  
 AM1 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , , ,  
 AONE= 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , , , ,  
 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , , , ,  
 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , , , ,  
 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , , , ,  
 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , , , ,  
 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, , , , , , ,  
 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,

TN2= 1460., 1960., 2060., 2260., 2460.,  
 2760., 2960., 3160., 3310., 4060.,  
 AM2 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , , ,  
 ATWO= 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,  
 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , , , ,

Table II- 8. CONCEPT 2: BETTER TURBINE THAN REQUIRED "AEO & OEI".

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TSHP=1460., 1935., 2110., 2260., 2460.,
      2660., 2760., 2960., 3110., 4060.,
AMSHP= 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , ,
SHPAV= 0.0015, 0.0042, 0.0111, 0.0307, 0.0429, 0.0654, , , , ,
      0.0132, 0.0173, 0.0428, 0.0640, 0.0878, 0.1197, , , , ,
      0.0297, 0.0352, 0.0635, 0.0887, 0.1236, 0.1659, , , , ,
      0.1358, 0.1469, 0.1835, 0.2206, 0.2693, 0.3289, , , , ,
      0.2968, 0.3150, 0.3643, 0.4053, 0.4637, 0.5442, , , , ,
      0.4938, 0.5215, 0.5929, 0.6515, 0.7277, 0.8248, , , , ,
      0.6125, 0.6460, 0.7297, 0.7989, 0.8887, 1.0031, , , , ,
      0.8738, 0.9159, 1.0252, 1.1152, 1.2313, 1.3784, , , , ,
      0.9916, 1.0374, 1.1661, 1.2656, 1.3952, 1.5590, , , , ,
      1.5052, 1.5682, 1.7655, 1.9216, 2.0906, 2.3242, , , , ,

TWD= 1460., 1935., 2110., 2260., 2460.,
      2660., 2760., 2960., 3110., 4060.,
AMWD = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , ,
WDOT= 0.0436, 0.0449, 0.0496, 0.0532, 0.0577, 0.0631, , , , ,
      0.0567, 0.0585, 0.0646, 0.0692, 0.0750, 0.0820, , , , ,
      0.0806, 0.0832, 0.0909, 0.0970, 0.1050, 0.1147, , , , ,
      0.1086, 0.1123, 0.1235, 0.1326, 0.1438, 0.1575, , , , ,
      0.1597, 0.1645, 0.1794, 0.1912, 0.2061, 0.2250, , , , ,
      0.2190, 0.2254, 0.2455, 0.2612, 0.2814, 0.3067, , , , ,
      0.2536, 0.2610, 0.2839, 0.3022, 0.3254, 0.3545, , , , ,
      0.3320, 0.3414, 0.3710, 0.3941, 0.4239, 0.4610, , , , ,
      0.3688, 0.3791, 0.4118, 0.4376, 0.4706, 0.5117, , , , ,
      0.5543, 0.5700, 0.6191, 0.6576, 0.7070, 0.7687, , , , ,

TN1= 1460., 1935., 2110., 2260., 2460.,
      2660., 2760., 2960., 3110., 4060.,
AM1 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , ,
AONE= 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.7007, 0.7007, 0.7007, 0.7007, 0.7007, 0.7007, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8600, 0.8600, 0.8600, 0.8600, 0.8600, 0.8600, , , , ,
      0.8991, 0.8991, 0.8991, 0.8991, 0.8991, 0.8991, , , , ,
      0.9383, 0.9383, 0.9383, 0.9383, 0.9383, 0.9383, , , , ,
      0.9585, 0.9585, 0.9585, 0.9585, 0.9585, 0.9585, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

TN2= 1460., 1935., 2110., 2260., 2460.,
      2660., 2760., 2960., 3110., 4060.,
AM2 = 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, , , , , ,
ATWO= 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,
      1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, , , , ,

```

**Table II- 9. CONCEPT 3: REHEAT BEFORE POWER TURBINE "AEO".**



## **APPENDIX III**

### **AE Calculated DMC For AE Baseline Tiltrotor Engine And Contingency Power Concepts**

**(24 Pages)**



AS812  
OPERATIONAL PROFILE  
FOR  
**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

51 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	760°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	735°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	728°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.057	0.172	0.239	0.265	0.282	0.284	0.288	0.290	0.293
SHOP VISIT PRICE	\$140,438	\$176,897	\$183,862	\$184,575	\$184,219	\$184,070	\$184,342	\$184,357	\$184,400
									\$184,646

27 OCTOBER 1995

AS812 - CONCEPT 1A  
OPERATIONAL PROFILE  
FOR

NASA SHORT HAUL CIVIL TILTROTOR

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

51 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	779°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	754°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	752°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.060	0.184	0.255	0.282	0.299	0.300	0.303	0.306	0.308	0.310
SHOP VISIT PRICE	\$125.626	\$159.604	\$165.842	\$168.051	\$165.321	\$164.739	\$164.710	\$164.710	\$164.798	\$164.990

**LCF RESERVE = \$13.45/CYCLE or \$15.82/HOUR**

AS812 - CONCEPT 1B  
OPERATIONAL PROFILE  
FOR

NASA SHORT HAUL CIVIL TILTROTOR

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

51 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	788°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	763°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	765°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.062	0.188	0.260	0.288	0.306	0.310	0.312	0.315
SHOP VISIT PRICE	\$121.778	\$155.101	\$160.826	\$161.042	\$160.089	\$159.359	\$159.313	\$159.423
SHOP VISIT PRICE								\$159.544

3 APRIL 1996

AS812 - CONCEPT 1C  
OPERATIONAL PROFILE  
FOR

**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

51 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS PER YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	791°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	767°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	769°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.062	0.190	0.263	0.291	0.308	0.309	0.312	0.315	0.317	0.319
SHOP VISIT PRICE	\$120,480	\$153,641	\$159,258	\$159,387	\$158,304	\$157,477	\$157,401	\$157,435	\$157,561	\$157,686

3 APRIL 1996

## NEW MODEL and DATABASE

	0.044	0.134	0.188	0.210	0.224	0.227	0.231	0.234	0.236	0.237
SHOP VISIT RATE										
SHOP VISIT PRICE	\$144,958	\$191,844	\$199,247	\$199,717	\$198,799	\$197,347	\$196,379	\$195,679	\$195,518	\$195,644

**LCF RESERVE = \$13.45/CYCLE or \$15.82/HOUR**

AS812 - CONCEPT 3  
OPERATIONAL PROFILE  
FOR

NASA SHORT HAUL CIVIL TILTROTOR

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

112 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	805°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	778°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	786°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

# OUTSIDE ENGINE SHOP & COMPONENT REPAIR

TOTAL MATERIAL	\$5.92	\$22.54	\$32.93	\$36.98	\$39.55	\$40.74	\$41.31	\$41.74	\$42.13	\$27.58	\$41.17	\$34.38
TOTAL LABOR	\$1.30	\$3.50	\$4.71	\$5.11	\$5.38	\$5.41	\$5.48	\$5.52	\$5.53	\$4.00	\$5.48	\$4.74
TOTAL DMC	\$7.22	\$26.04	\$37.64	\$42.10	\$44.93	\$45.36	\$46.19	\$46.79	\$47.26	\$31.58	\$46.65	\$39.12

SSHOP VISIT RATE	0.041	0.126	0.177	0.198	0.212	0.215	0.219	0.222	0.224
SSHOP VISIT PRICE	\$142,560	\$180,571	\$188,398	\$189,720	\$189,360	\$188,689	\$188,644	\$188,868	\$189,764

AS812 - CONCEPT 2  
OPERATIONAL PROFILE  
FOR

**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

112 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS PER YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	796°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	770°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	761°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.043	0.131	0.183	0.205	0.219	0.222	0.226	0.229	0.230	0.232
SHOP VISIT PRICE	\$130,716	\$167,068	\$173,778	\$174,792	\$174,308	\$173,462	\$173,139	\$173,123	\$173,326	\$173,621

3 APRIL 1998

AS812 - CONCEPT 1C  
OPERATIONAL PROFILE  
FOR

NASA SHORT HAUL CIVIL TILTROTOR

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

112 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	791°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	767°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	769°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.042	0.130	0.182	0.203	0.217	0.220	0.224	0.227	0.229	0.230
SHOP VISIT PRICE	\$131,953	\$168,412	\$175,284	\$176,320	\$175,931	\$175,210	\$174,984	\$174,948	\$175,227	\$175,509

**LCF RESERVE = \$13.45/CYCLE or \$15.82/HOUR**

**AS812 - CONCEPT 1B  
OPERATIONAL PROFILE  
FOR**

**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

112 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	788°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	763°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	765°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.041	0.127	0.178	0.199	0.213	0.216	0.220	0.223	0.224	0.226
SHOP VISIT PRICE	\$135,540	\$172,362	\$179,773	\$181,012	\$180,688	\$180,096	\$180,086	\$180,352	\$180,694	\$181,036

**LCF RESERVE = \$13.45/CYCLE or \$15.82/HOUR**

AS812 - CONCEPT 1A  
OPERATIONAL PROFILE  
FOR

**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

112 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	779°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	754°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	752°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

## OUTSIDE ENGINE SHOP & COMPONENT REPAIR

TOTAL MATERIAL	\$6.12	\$22.87	\$33.48	\$37.68	\$40.35	\$40.87	\$41.76	\$42.45	\$42.98	\$43.40	\$28.10	\$42.29	\$35.20
TOTAL LABOR	\$1.27	\$3.40	\$4.58	\$4.98	\$5.25	\$5.26	\$5.31	\$5.35	\$5.37	\$5.39	\$3.90	\$5.34	\$4.62
TOTAL DMC	\$7.40	\$26.28	\$38.06	\$42.66	\$45.60	\$46.13	\$47.07	\$47.80	\$48.35	\$48.79	\$32.00	\$47.63	\$39.81

**LCF RESERVE = \$13.45/CYCLE or \$7.21/HOUR**

**AS812**  
**OPERATIONAL PROFILE**  
**FOR**  
**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

112 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	760°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	735°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	728°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

BASE112

27 OCTOBER 1995

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.064	0.195	0.270	0.299	0.317	0.317	0.320	0.323	0.325	0.327
SHOP VISIT PRICE	\$133,583	\$175,299	\$181,413	\$181,252	\$179,211	\$177,405	\$176,897	\$176,748	\$176,659	\$176,583

**LCF RESERVE = \$13.45/CYCLE or \$15.82/HOUR**

AS812 - CONCEPT 3  
OPERATIONAL PROFILE  
FOR

**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

51 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	805°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	778°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	786°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

NEW MODEL and DATABASE

## NEW MODEL and DATABASE

SHOP VISIT RATE	0.060	0.184	0.255	0.282	0.300	0.301	0.304	0.307	0.309	0.311
SHOP VISIT PRICE	\$131.353	\$166.024	\$172.339	\$172.715	\$171.819	\$171.144	\$171.231	\$171.449	\$171.715	\$171.974

**LCF RESERVE = \$13.45/CYCLE or \$15.82/HOUR**

AS812 - CONCEPT 2  
OPERATIONAL PROFILE  
FOR

**NASA SHORT HAUL CIVIL TILTROTOR**

AIRCRAFT DELIVERY SCHEDULE	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
	1	0	0	0	0	0	0	0	0	0

51 MINUTE FLIGHT	95% AIRLINE MATERIAL EFFICIENCY
2,500 AIRCRAFT HOURS Per YEAR	95% VENDOR MATERIAL EFFICIENCY
1996 VINTAGE ENGINE	100% AIRLINE LABOR EFFICIENCY
10 YEAR STUDY	100% VENDOR LABOR EFFICIENCY
\$15 LINE LABOR RATE	NO SPARE ENGINES
\$65 SHOP LABOR RATE	796°C AVG TAKE OFF TEMP
\$65 VENDOR LABOR RATE	770°C AVG CLIMB TEMP
1995 CONSTANT DOLLARS	761°C AVG CRUISE TEMP
MAINTENANCE TASK LEVEL 6	MAX TAKEOFF, MAX R/C

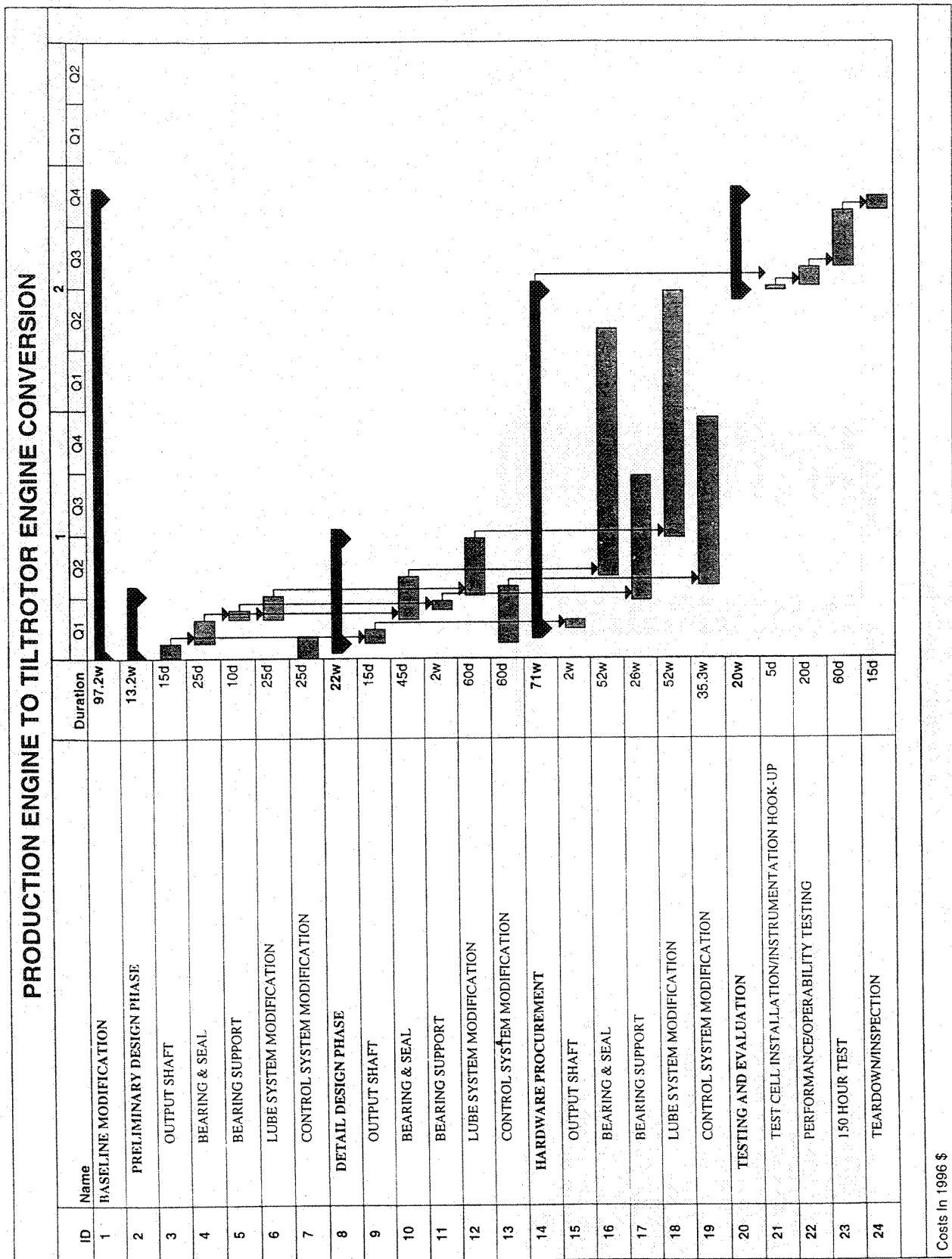
NEW MODEL and DATABASE

**APPENDIX IV**

**AE Development Program  
Schedule and Budget**

**(13 Pages)**





**Estimated Budget Report  
Baseline Engine Modification**

ID	Task Name	Other \$	Total Cost
24	TEARDOWN/INSPECTION	\$0.00	\$52,800.00
23	150 HOUR TEST	\$0.00	\$132,000.00
22	PERFORMANCE/OPERABILITY TESTING	\$0.00	\$52,800.00
21	TEST CELL INSTALLATION/INSTRUMENTATION HOOK-UP	\$0.00	\$13,200.00
19	CONTROL SYSTEM MODIFICATION	\$0.00	\$100,000.00
18	LUBE SYSTEM MODIFICATION	\$50.00	\$50,050.00
17	BEARING SUPPORT	\$0.00	\$2,000.00
16	BEARING & SEAL	\$0.00	\$10,000.00
15	OUTPUT SHAFT	\$0.00	\$20,000.00
13	CONTROL SYSTEM MODIFICATION	\$0.00	\$158,400.00
12	LUBE SYSTEM MODIFICATION	\$0.00	\$132,000.00
11	BEARING SUPPORT	\$0.00	\$8,800.00
10	BEARING & SEAL	\$0.00	\$79,200.00
9	OUTPUT SHAFT	\$0.00	\$19,800.00
7	CONTROL SYSTEM MODIFICATION	\$0.00	\$44,000.00
6	LUBE SYSTEM MODIFICATION	\$0.00	\$44,000.00
5	BEARING SUPPORT	\$0.00	\$8,800.00
4	BEARING & SEAL	\$0.00	\$44,000.00
3	OUTPUT SHAFT	\$0.00	\$19,800.00
		<b>\$50.00</b>	<b>\$991,650.00</b>

# WATER / METHANOL INJECTION

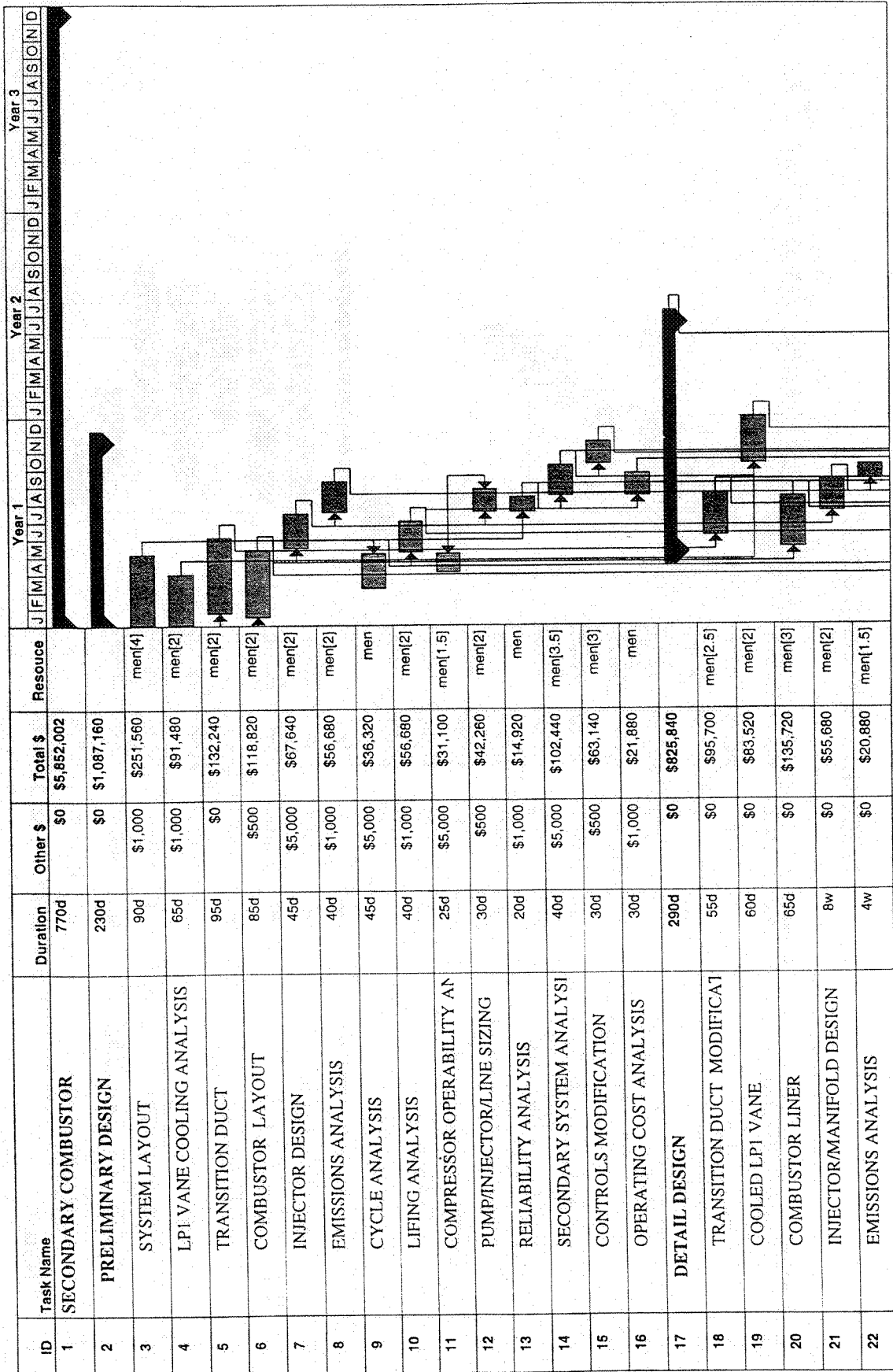
ID	Task Name	Duration	Other \$	Total \$	Resource	Year 1	Year 2	Year 3	Year 4
1	WATER METHANOL INJECTION	958d	\$0	\$2,803,333					
2	PRELIMINARY DESIGN	95d	\$0	\$239,282					
3	SYSTEM LAYOUT	25d	\$0	\$34,974	men[2]				
4	ANALYSIS	95d	\$0	\$146,280					
5	SECONDARY SYSTEM ANALYSIS	25d	\$5,000	\$39,974	men[2]				
6	COMPRESSOR OPERABILITY ANAL	15d	\$5,000	\$20,791	men[1.5]				
7	CYCLE ANALYSIS	15d	\$5,000	\$15,527	men				
8	LIFING ANALYSIS	20d	\$5,000	\$33,014	men[2]				
9	RELIABILITY ANALYSIS	20d	\$1,000	\$15,007	men				
10	OPERATING COST ANALYSIS	30d	\$1,000	\$21,967	men				
11	PUMP/INJECTOR/LINE SIZING	10d	\$1,000	\$15,094	men[2]				
12	CONTROLS MODIFICATION	30d	\$1,000	\$42,934	men[2]				
13	DETAIL DESIGN	90d	\$0	\$326,943					
14	INLET HOUSING MODIFICATIONS	15d	\$0	\$15,791	men[1.5]				
15	INJECTOR/MANIFOLD DESIGN	25d	\$0	\$34,974	men[2]				
16	PUMP DESIGN	45d	\$0	\$94,221	men[3]				
17	PRELIMINARY SYSTEM MOCK UP	10d	\$0	\$21,141	men[3]				
18	PIPE DESIGN	20d	\$0	\$28,014	men[2]				
19	CONTROLS MODIFICATIONS	30d	\$0	\$41,934	men[2]				
20	H2O/METH INJECTION RIG DESIGN	1d	\$0	\$0					
21	ANALYSIS	90d	\$0	\$90,868					
22	LIFING ANALYSIS	30d	\$5,000	\$46,934	men[2]				
23	RELIABILITY ANALYSIS	30d	\$1,000	\$21,967	men				
24	OPERATING COST ANALYSIS	30d	\$1,000	\$21,967	men				
25	HARDWARE PROCUREMENT	600d	\$0	\$1,143,011					
26	ENGINE HARDWARE	600d	\$500,000	\$917,687	men				

Costs In 1996 \$

Estimated Budget Report  
Better Turbine than Required

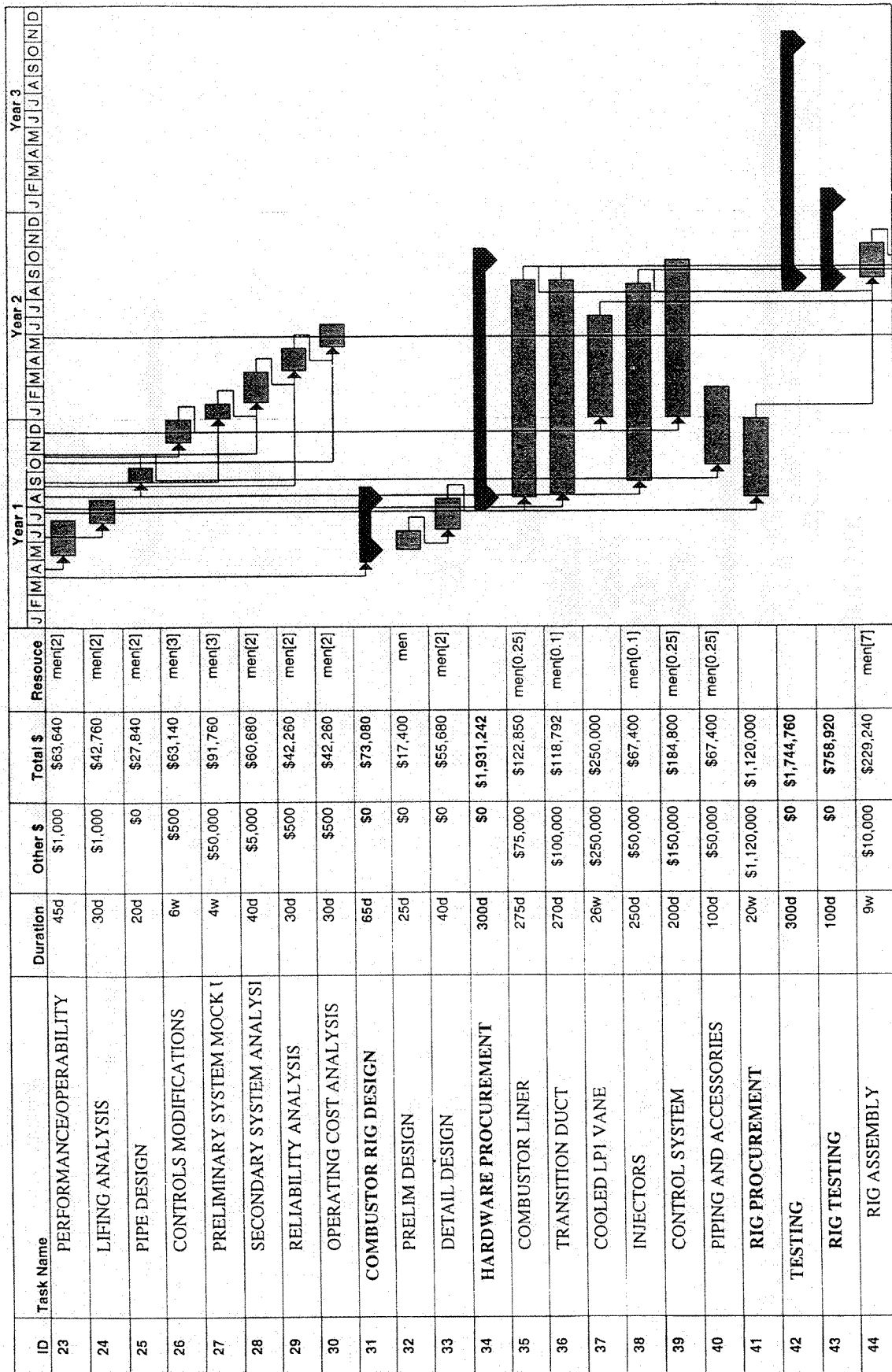
ID	Task Name	Other \$	Total Cost
1	TURBINE OVERDESIGN	\$0	\$1,549,724
2	BI-CAST NOZZLE DESIGN	\$0	\$345,080
3	THERMAL ANALYSIS	\$5,000	\$98,960
4	STRESS ANALYSIS	\$5,000	\$98,960
5	LAYOUT	\$1,000	\$74,080
6	DETAIL DESIGN	\$0	\$73,080
7	OTHER COMPONENT DESIGN	\$0	\$418,600
8	COMPONENT LIFE REVIEW	\$1,000	\$209,800
9	REVISED DETAIL DRAWINGS	\$0	\$208,800
10	HARDWARE PROCUREMENT	\$0	\$195,924
11	BLADES	\$0	\$43,500
12	CASTING	\$0	\$34,800
13	MACHINING	\$0	\$8,700
14	DISKS	\$0	\$40,368
15	FORGING	\$0	\$34,800
16	MACHINING	\$0	\$5,568
17	NOZZLES	\$0	\$112,056
18	FIRST NOZZLE	\$0	\$73,776
19	CASTING	\$0	\$69,600
20	MACHINING	\$0	\$4,176
21	SECOND NOZZLE	\$0	\$38,280
22	CASTING	\$0	\$34,800
23	MACHINING	\$0	\$3,480
24	BASELINE ENGINE	\$0	\$0
25	TESTING	\$0	\$506,600
26	INSTRUMENTATION & ASSEMBLY	\$100,000	\$152,200
27	1000 CYCLE TEST	\$250,000	\$354,400
28	REPORTING	\$0	\$83,520
29	DESIGN REPORT	\$0	\$41,760
30	TEST REPORT	\$0	\$41,760
		<b>\$362,000</b>	<b>\$1,549,724</b>

# Secondary Combustor



Costs in 1996 \$

## Secondary Combustor



Costs in 1996 \$

ID	Task Name	Duration	Other \$	Total \$	Resource
45	RIG TESTING	11w	\$300,000	\$529,680	men[6]
46	ASSEMBLY/INSTRUMENTATION	200d	\$0	\$985,840	
47	INSTRUMENTATION	60d	\$10,000	\$72,640	men[1.5]
48	ASSEMBLY	25d	\$10,000	\$27,400	men
49	MODIFIED CONTROL	10d	\$15,000	\$28,920	men[2]
50	FINAL MOCK-UP	15d	\$100,000	\$131,320	men[3]
51	HARDWARE MODIFICATION	15d	\$20,000	\$51,320	men[3]
52	ASSEMBLY COMPLETE	0d	\$0	\$0	
53	ENGINE TESTS	110d	\$0	\$674,240	
54	TEST CELL INSTALLATION	15d	\$5,000	\$36,320	men[3]
55	PERFORMANCE/OPEA	20d	\$200,000	\$241,760	men[3]
56	150 HOUR TEST	60d	\$250,000	\$354,400	men[2.5]
57	TEARDOWN/INSPECTIO	15d	\$0	\$41,760	men[4]
58	DATA ANALYSIS	390d	\$0	\$189,920	
59	PERFORMANCE/OPERABILITY F	24d	\$500	\$42,260	men[2.5]
60	DESIGN REPORT	30d	\$500	\$84,020	men[4]
61	HARDWARE INSPECTION REPOI	25d	\$500	\$52,700	men[3]
62	FINAL SUMMARY REPORT	10d	\$500	\$10,940	men[1.5]

NASA/CR—2003-212465

# Estimated Budget Report SECONDARY COMBUSTOR CONCEPT

ID	Task Name	Other \$	Total Cost
1	SECONDARY COMBUSTOR	\$0	\$5,177,002
2	PRELIMINARY DESIGN	\$0	\$1,087,160
3	SYSTEM LAYOUT	\$1,000	\$251,560
4	LP1 VANE COOLING ANALYSIS	\$1,000	\$91,480
5	TRANSITION DUCT	\$0	\$132,240
6	COMBUSTOR LAYOUT	\$500	\$118,820
7	INJECTOR DESIGN	\$5,000	\$67,640
8	EMISSIONS ANALYSIS	\$1,000	\$56,680
9	CYCLE ANALYSIS	\$5,000	\$36,320
10	LIFING ANALYSIS	\$1,000	\$56,680
11	COMPRESSOR OPERABILITY ANALYSIS	\$5,000	\$31,100
12	PUMP/INJECTOR LINE SIZING	\$500	\$42,260
13	RELIABILITY ANALYSIS	\$1,000	\$14,920
14	SECONDARY SYSTEM ANALYSIS	\$5,000	\$102,440
15	CONTROLS MODIFICATION	\$500	\$63,140
16	OPERATING COST ANALYSIS	\$1,000	\$21,880
17	DETAIL DESIGN	\$0	\$825,840
18	TRANSITION DUCT MODIFICATIONS	\$0	\$95,700
19	COOLED LP1 VANE	\$0	\$83,520
20	COMBUSTOR LINER	\$0	\$135,720
21	INJECTOR/MANIFOLD DESIGN	\$0	\$55,680
22	EMISSIONS ANALYSIS	\$0	\$20,880
23	PERFORMANCE/OPERABILITY	\$1,000	\$63,640
24	LIFING ANALYSIS	\$1,000	\$42,760
25	PIPE DESIGN	\$0	\$27,840
26	CONTROLS MODIFICATIONS	\$500	\$63,140
27	PRELIMINARY SYSTEM MOCK UP	\$50,000	\$91,760
28	SECONDARY SYSTEM ANALYSIS	\$5,000	\$60,680
29	RELIABILITY ANALYSIS	\$500	\$42,260
30	OPERATING COST ANALYSIS	\$500	\$42,260
31	COMBUSTOR RIG DESIGN	\$0	\$73,080
32	PRELIM DESIGN	\$0	\$17,400
33	DETAIL DESIGN	\$0	\$35,680
34	HARDWARE PROCUREMENT	\$0	\$1,256,242
35	COMBUSTOR LINER	\$0	\$47,850
36	TRANSITION DUCT	\$0	\$18,792
37	COOLED LP1 VANE	\$0	\$0
38	INJECTORS	\$0	\$17,400
39	CONTROL SYSTEM	\$0	\$34,800
40	PIPING AND ACCESSORIES	\$0	\$17,400
41	BASELINE ENGINE	\$0	\$0
42	RIG PROCUREMENT	\$1,120,000	\$1,120,000
43	TESTING	\$0	\$1,744,760
44	RIG TESTING	\$0	\$736,920
45	RIG ASSEMBLY	\$10,000	\$229,240
46	RIG TESTING	\$200,000	\$529,680
47	ASSEMBLY/INSTRUMENTATION	\$0	\$965,840
48	INSTRUMENTATION	\$10,000	\$72,640
49	ASSEMBLY	\$10,000	\$27,400
50	MODIFIED CONTROL	\$15,000	\$28,920
51	FINAL MOCK-UP	\$100,000	\$131,320
52	HARDWARE MODIFICATIONS	\$20,000	\$51,320
53	ASSEMBLY COMPLETE	\$0	\$0
54	ENGINE TESTS	\$0	\$674,240
55	TEST CELL INSTALLATION/INSTRUMENTATION HOOK-UP	\$5,000	\$36,320
56	PERFORMANCE/OPERABILITY TESTING	\$200,000	\$241,760
57	150 HOUR TEST	\$250,000	\$354,400
58	TEARDOWN/INSPECTION	\$0	\$41,760
59	DATA ANALYSIS	\$0	\$109,920
60	PERFORMANCE/OPERABILITY REPORT	\$500	\$42,260
61	DESIGN REPORT	\$500	\$84,020
62	HARDWARE INSPECTION REPORT	\$500	\$52,700
63	FINAL SUMMARY REPORT	\$500	\$10,940
		\$2,128,000	\$5,177,002

# WATER / METHANOL INJECTION

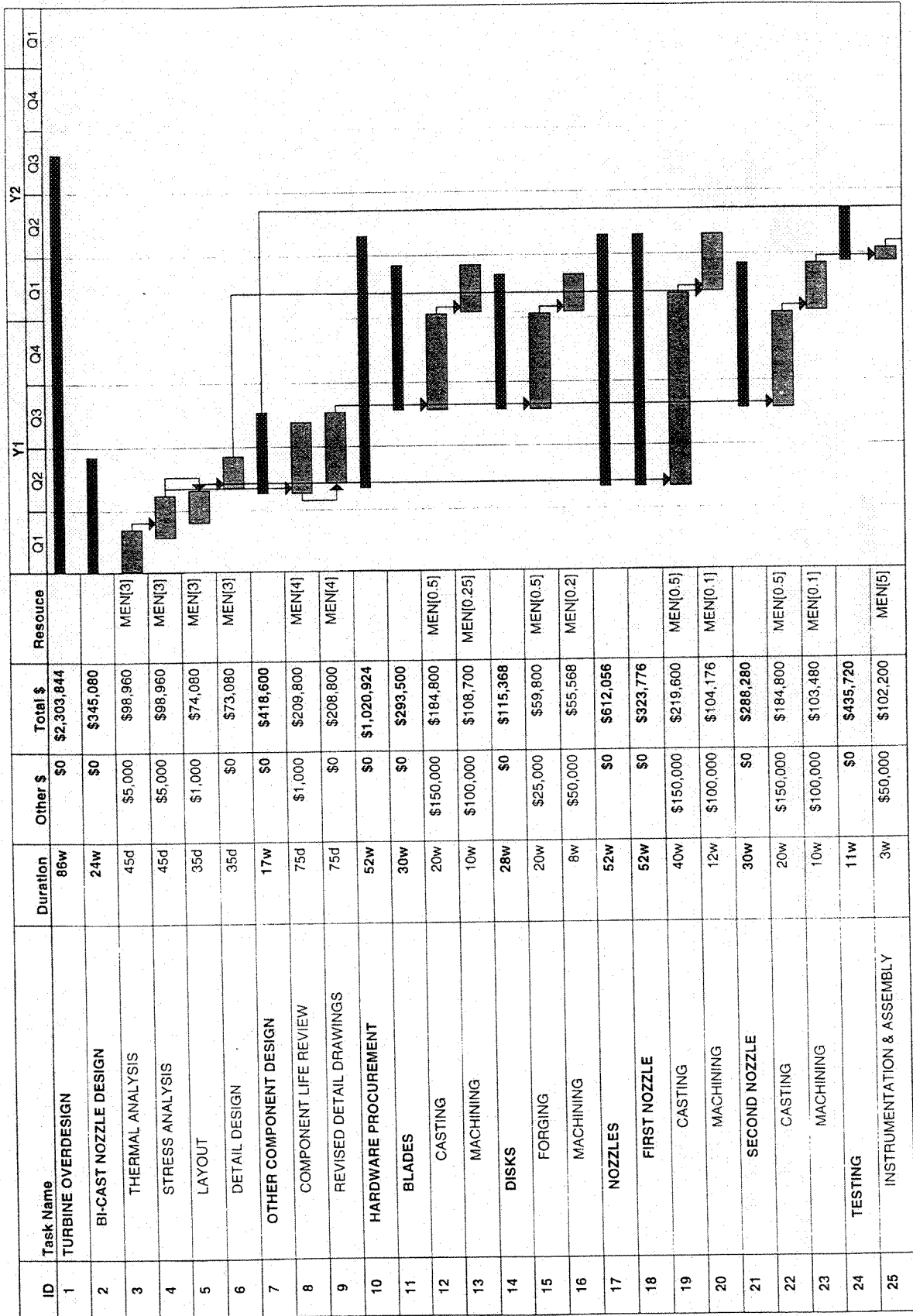
ID	Task Name	Duration	Other \$	Total \$	Resource	Year 1	Year 2	Year 3	Year 4
27	RIG HARDWARE	360d	\$100,000	\$225,324	men[0.5]				
28	ASSEMBLY/INSTRUMENTATION	100d	\$0	\$430,472					
29	INSTRUMENTATION	60d	\$50,000	\$112,771	men[1.5]				
30	MOD INLET INSTALLATION	5d	\$50,000	\$53,567	men				
31	MODIFIED CONTROL	40d	\$0	\$116,028	men[0]				
32	CONTROL INSTRUMENTATION	30d	\$10,000	\$51,934	men[2]				
33	BENCH TESTING	10d	\$50,000	\$64,094	men[2]				
34	FINAL MOCK-UP	3d	\$25,000	\$31,525	men[3]				
35	HARDWARE MODIFICATIONS	15d	\$75,000	\$106,581	men[3]				
36	ASSEMBLY COMPLETE	0d	\$10,000	\$10,000					
37	TESTING	98d	\$0	\$564,622					
38	TEST CELL INSTALLATION/INSTRUMENTATION	3d	\$5,000	\$15,875	men[5]				
39	PERFORMANCE/OPERABILITY TESTING	20d	\$100,000	\$142,021	men[3]				
40	150 HOUR TEST	60d	\$250,000	\$354,618	men[2.5]				
41	TEARDOWN/INSPECTION	15d	\$10,000	\$52,108	men[4]				
42	DATA ANALYSIS	110d	\$0	\$99,006					
43	PERFORMANCE/OPERABILITY REPORT	25d	\$1,000	\$35,974	men[2]				
44	HARDWARE INSPECTION REPORT	25d	\$0	\$52,461	men[3]				
45	FINAL SUMMARY REPORT	10d	\$0	\$10,571	men[1.5]				

Costs in 1996 \$

Estimated Budget Report  
Water Methanol Concept

ID	Task Name	Other \$	Total Cost
1	WATER METHANOL INJECTION	\$0	\$2,303,333
2	PRELIMINARY DESIGN	\$0	\$239,282
3	SYSTEM LAYOUT	\$0	\$34,974
4	ANALYSIS	\$0	\$146,280
5	SECONDARY SYSTEM ANALYSIS	\$5,000	\$39,974
6	COMPRESSOR OPERABILITY ANALYSIS	\$5,000	\$20,791
7	CYCLE ANALYSIS	\$5,000	\$15,527
8	LIFING ANALYSIS	\$5,000	\$33,014
9	RELIABILITY ANALYSIS	\$1,000	\$15,007
10	OPERATING COST ANALYSIS	\$1,000	\$21,967
11	PUMP/INJECTOR/LINE SIZING	\$1,000	\$15,094
12	CONTROLS MODIFICATION	\$1,000	\$42,934
13	DETAIL DESIGN	\$0	\$326,943
14	INLET HOUSING MODIFICATIONS	\$0	\$15,791
15	INJECTOR/MANIFOLD DESIGN	\$0	\$34,974
16	PUMP DESIGN	\$0	\$94,221
17	PRELIMINARY SYSTEM MOCK UP	\$0	\$21,141
18	PIPE DESIGN	\$0	\$28,014
19	CONTROLS MODIFICATIONS	\$0	\$41,934
20	H2O/METH INJECTION RIG DESIGN	\$0	\$0
21	ANALYSIS	\$0	\$90,868
22	LIFING ANALYSIS	\$5,000	\$46,934
23	RELIABILITY ANALYSIS	\$1,000	\$21,967
24	OPERATING COST ANALYSIS	\$1,000	\$21,967
25	HARDWARE PROCUREMENT	\$0	\$643,011
26	ENGINE HARDWARE	\$0	\$417,687
27	BASELINE ENGINE	\$0	\$0
28	RIG HARDWARE	\$100,000	\$225,324
29	ASSEMBLY/INSTRUMENTATION	\$0	\$430,472
30	INSTRUMENTATION	\$50,000	\$112,771
31	MOD INLET INSTALLATION	\$50,000	\$53,567
32	MODIFIED CONTROL	\$0	\$116,028
33	CONTROL INSTRUMENTATION	\$10,000	\$51,934
34	BENCH TESTING	\$50,000	\$64,094
35	FINAL MOCK-UP	\$25,000	\$31,525
36	HARDWARE MODIFICATIONS	\$75,000	\$106,581
37	ASSEMBLY COMPLETE	\$10,000	\$10,000
38	TESTING	\$0	\$564,622
39	TEST CELL INSTALLATION/INSTRUMENTATION HOOK-UP	\$5,000	\$15,875
40	PERFORMANCE/OPERABILITY TESTING	\$100,000	\$142,021
41	150 HOUR TEST	\$250,000	\$354,618
42	TEARDOWN/INSPECTION	\$10,000	\$52,108
43	DATA ANALYSIS	\$0	\$99,006
44	PERFORMANCE/OPERABILITY REPORT	\$1,000	\$35,974
45	HARDWARE INSPECTION REPORT	\$0	\$52,461
46	FINAL SUMMARY REPORT	\$0	\$10,571
		\$767,000	\$2,303,333

# TURBINE OVERDESIGN

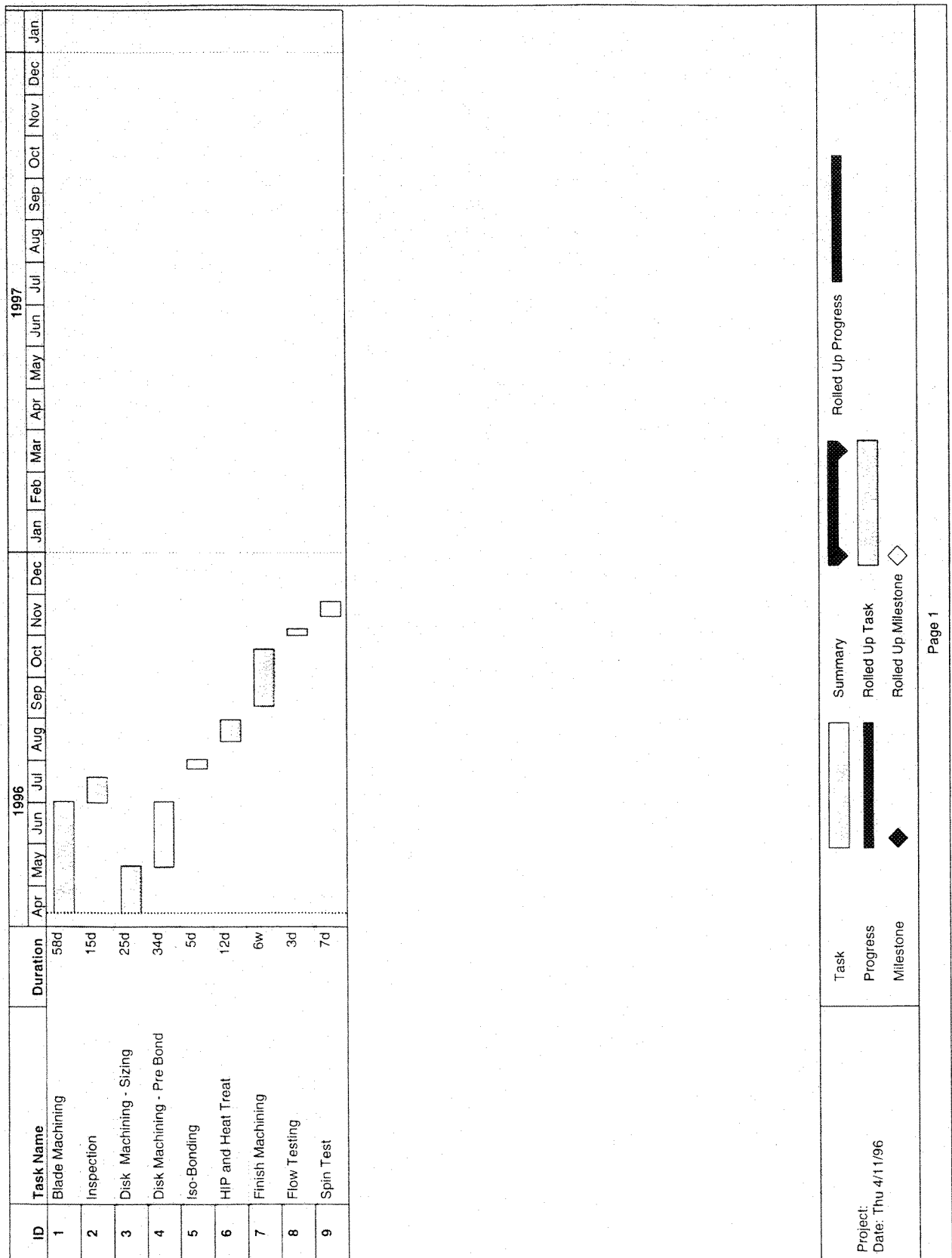


Costs In 1996 \$

# TURBINE OVERDESIGN

ID	Task Name	Duration	Other \$	Total \$	Resource	Y1				Y2			
						Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
26	1000 CYCLE TEST	8w	\$250,000	\$333,520	MEN[3]								
27	REPORTING	12w	\$0	\$83,520									
28	DESIGN REPORT	30d	\$0	\$41,760	MEN[2]								
29	TEST REPORT	30d	\$0	\$41,760	MEN[2]								

Costs In 1996 \$



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6. AUTHOR(S)  John Wait				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  AlliedSignal Engines 111 S. 34th Street Phoenix, Arizona 85072-2181			8. PERFORMING ORGANIZATION REPORT NUMBER  E-14003	
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13. ABSTRACT (Maximum 200 words)  AlliedSignal Engines (AE) defined a number of concepts that significantly increased the horsepower of a turboshaft engine to accommodate the loss of an engine and enable the safe landing of a twin-engined, 40-passenger, short haul civil tiltrotor. From these concepts, "Water/Methanol Injection," a "Better Power Turbine Than Required," and a "Secondary Combustor For Interturbine Reheat" were chosen, based on system safety and economics, for more detailed examination. Engine performance, mission, and cost analysis of these systems indicated contingency power levels of 26 to 70 percent greater than normal rated takeoff could be attained for short durations, thus enabling direct operating cost savings between 2 and 6 percent.				
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